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A Joint Program for Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing

Soil Moisture

November 1980

SOIL MOISTURE PROJECT EVALUATION WORKSHOP

Beltsville Agricultural Research Center
June 16–17, 1980

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16. Abstract

The first AgRISTARS Soil Moisture Project Evaluation Workshop was held at the Beltsville Agriculture Research Center, Beltsville, Maryland, on June 16-17, 1980. The purpose of the workshop was to provide a means for technical interchange among Soil Moisture Project investigators. Papers presented at the workshop and included in these workshop proceedings were given by Tom Jackson (SEA/AR), Richard Newton (Texas A&M University), Jack Paris (NASA/Johnson Space Center), Eni Njoku (Jet Propulsion Laboratory), Bill Waite and Don Scott (University of Arkansas), and Gerry Bradley (University of Kansas).

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active microwave	agriculture

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SOIL MOISTURE PROJECT
EVALUATION WORKSHOP
BELTSVILLE AGRICULTURAL RESEARCH CENTER
BELTSVILLE, MD

June 16-17, 1980

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June 16, 17 Soil Moisture Workshop Summary

The first AgRISTARS Soil Moisture Workshop was held at Beltsville Agriculture Research Center on June 16, 17, 1980. Appendix 1 is a list of the attendees and an agenda.

The tone of an informal, information exchange was set by the Chairman, Richard Gilbert, USDA/SCS, Soil Moisture Project Manager for AgRISTARS. Richard Gilbert asked the attendees to remember, during their deliberations, that the AgRISTARS Soil Moisture Project should have an LSAT during the AgRISTARS program. Future work should be discussed in the context of why it was necessary for or how it would support potential LSATs.

Michael Calabrese, NASA/Hq, set the AgRISTARS Soil Moisture research effort in the context of the Joint Soil Moisture Program. He indicated that, even though AgRISTARS was providing primary motivation and funding in the Joint Soil Moisture Program, complimentary research is occuring in the areas of Water Resources and Climate that the group attending this Workshop should be cognizant of.

Albert Rango, NASA/GSFC, stated that the Integrated Soil Moisture Program Plan was waiting NASA Headquarters approval prior to publication and distribution. It was stated that the attendees at this workshop would be on the distribution list. Al Rango also stated that a general AgRISTARS meeting is being scheduled in November 1980.

Ted Engman, USDA/SEA-AR, the host for the workshop provided an excellent justification for soil moisture research activities when he stated that meteorological droughts are not always a good indicator of agricultural drought. This was amply demonstrated in the 1977 harvest of winter wheat in the U.S. Great Plains when a bumper crop was harvested even though meteorological indicators showed a serious drought was in progress.

After the introductory remarks, the various research groups made presentations. Many of these presentations were overall status reviews that were meant to show the status of their soil moisture program and the research direction they, as scientists, feel would be practical and should be pursued during the coming year. There was very little emphasis on what had been or was being accomplished with AgRISTARS funding. Since most university ground data collection efforts are scheduled for the summer, this lack of emphasis on AgRISTARS results is understandable. Copies of presentation material and author developed commentary (where available) are included as Appendices 2 through 7. Highlights of the presentations follow.

Tom Jackson, USDA/SEA-AR, in addition to discussing the emphasis of the FY 80 work and relating this emphasis to the AgRISTARS Soil Moisutre Project tasks, reported on the results of data collected by aircraft over Chickasha, OK; Tifton, GA; and Taylor Creek, FL.

Of particular interest was the analysis of the spatial variability of soil moisture as a function of terrain relief. Using data from Phoenix and from Hand County, it was found that on flat fields and on rolling fields no discernible soil moisture patterns exist; on flat sloping fields strong soil moisture patterns exist. This infers that sampling procedures to determine aggregate soil moisture ground truth should be terrain dependent.

Tom Jackson also reported on the value of soil moisture information to develop stream flow information. Neutron probe soil moisture data was used. The conclusion of the study was that, in general, soil moisture observations used to correct or update model simulations improve the estimate of annual runoff. The benefit of the improvement still needs to be developed to help in an assessment of cost effectiveness.

Richard Newton, Texas A&M University, discussed the approach the scientists at TAMU are taking to the soil moisture research effort. The approach is basically two pronged:

1. Understand the Energy/Scene Interactions
2. Understand what can be done with satellite data.

In developing the understanding of the energy/scene interactions, significant efforts in the development and verification of soil water budget models and soil water profile/soil temperature profile models have been made. Efforts to understand the effects of surface roughness, vegetation cover, soil texture and climate are being emphasized. As part of this understanding, development activity models are being developed to simulate satellite scenes.

In related (not AgRISTARS funded) efforts, an empirical understanding of what can now be done to determine soil moisture information with existing satellite data is being pursued.

Jack Paris, NASA/JSC, discussed the problems connected with getting the Colby County data processed. He also discussed the cooperative effort that was being started with Prairie View A&M. Prairie View A&M is receiving a grant from NASA Headquarters and wanted to do some fundamental remote sensing research with that funding. They are planning to work with JSC to study the effects of row direction on the microwave return. Measurements are to start during the summer of 1980 and the data is to be analyzed in near real time.

Jack Paris also discussed the models they are planning to use in their soil moisture sensitivity analyses. The Van Bavel model is to be the first model used.

Eni Njoku, JPL, discussed the modeling and analysis effort at JPL and the assistance being provided at UCSB. He stated that the combination of the thermal model and microwave was complete and showed comparisons of the measured soil moisture with depth and the model calculated soil moisture with depth.

Eni Njoku also discussed use of a technique developed for planetary roughness determination for determining the field roughness parameters for incorporation in the models.

Tom Schmugge, NASA/GSFC, reported on the joint activites with USDA/SEA-AR. GSFC is responsible for the aircraft data and data reduction, SEA-AR is primarily responsible for ground data collection. Analysis and reporting is a joint activity. In addition, he reported that two new universities were becoming involved in Soil Moisture research activities; Roger Lang, at George Washington University, and Dr. Kong, at MIT.

Bill Waite and Don Scott discussed their measurement and analyses efforts at the University of Arkansas. They are working on the problem of determining how a crust or soil layer affects the microwave return. These measurements are being taken under laboratory conditions where the moisture and the layering can be closely controlled.

Gerry Bradley, University of Kansas, while discussing their activities presented correlation of the aircraft and Colby County, Kansas data for Day 1. When truck data could be used to determine the bias between the aircraft scatterometers and the truck-radar and the bias was removed from the scatterometer, the truck-radar and aircraft regressions have slopes near unity and a near zero y-intercept. Since it is known that truck-radar correlates well with soil moisture, these results show scientifically that fairly accurate soil moisture measurements can be made with calibrated aircraft and spacecraft radar data.

The above are only highlights of the status presentation. More details of the individual research activities and the status of those activities can be found in the Appendices.

During the general discussion, it was agreed that the major effort in FY 81 should be a continuation of previous activities. A large scale coordinated research activity demanding large scale, timely aircraft over-flights like Colby County, Kansas was premature. Aircraft flights in FY 81 should be aimed at acquiring specific data to solve defined questions. Most of those questions would be developed by modelers in the analysis efforts. While the goal of an LSAT during AgRISTARS was acknowledged, most of the researchers believed the definition of a potential LSAT in terms more than "a generalized soil moisture map" was premature and that the definition of an LSAT could not be accomplished within the Soil Moisture Project--a more meaningful LSAT could be developed in conjunction with another AgRISTARS project such as Yield, Early Warning or possibly Conservation.

APPENDIX A
ATTENDEES AND AGENDA

AgRISTARS
SOIL MOISTURE PROJECT
EVALUATION WORKSHOP
BELTSVILLE AGRICULTURAL RESEARCH CENTER
BUILDING --7, BARC WEST
BELTSVILLE, MD

June 16-17, 1980

Monday, June 16

Opening Remarks	Dick Gilbert Mike Calabrese Al Rango Ted Engman
USDA/SEA-AR	Tom Jackson
Texas A&M University	Richard Newton
Johnson Space Center	Jack Paris
University of Arkansas	Bill Waite
Jet Propulsion Laboratory	Don Scoll Eni Njoku
University of Kansas	Gerry Bradley

Tuesday, June 17

FY 1981 Objectives Review	Tom Schmugge
Project Evaluation and Discussion	All
Adjourn	

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APPENDIX B

PRESENTATION BY TOM JACKSON SEA/AR

AgRISTARS SOIL MOISTURE PROJECT

USDA-SEA-AR Hydrology Laboratory and NASA-GSFC

Cooperative Research Evaluation Workshop Report

June 16, 1980

Specific research items described in the AgRISTARS Soil Moisture Project Implementation Plan (Gilbert, 1980) have been resolved into a program of research aimed at the application and implementation of remote sensing of soil moisture in hydrology and agriculture.

Research has and will be directed at three problems which will in combination support the application and implementation of remote sensing of soil moisture. These problems are:

(1) Identification and development of relationships between remotely sensed data and soil moisture.

(2) Development of procedures for utilizing remotely sensed soil moisture data in conventional applications.

(3) Evaluation of the utility of soil moisture observations in conventional applications.

These 3 problem areas represent a different approach to the objective than that outlined in the tasks of the Implementation Plan. However, these 3 areas include all of the tasks as well as others which have been identified in the course of the research.

The following sections summarize the work in each of these areas to date and present some of the research that will be conducted in FY 81.

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1. Identification and Development of Relationships Between Remotely Sensed Data and Soil Moisture.

Research in this area is aimed at developing a complete set of relationships between remotely sensed measurements and soil moisture. This work is designed to extend the previously developed data sets to other conditions and, therefore, emphasizes vegetation, soil, and spatial effects.

During the past year research has been conducted using both truck and aircraft mounted sensors. The emphasis in these experiments has been on the microwave region of the electromagnetic spectrum. In addition, a literature survey of methods for soil moisture determination has been conducted as a step in the comparison of the methods (Schmugge et al, 1980).

Remote measurements of soil moisture contents over bare fields and fields covered with grass, soybeans, and corn were made during October 1979 with L and C band microwave radiometers mounted on a mobile truck. The radiometric measurements covered the range of incident angles from 10° to 70° in 10° steps. The measured values of brightness temperature for bare fields were compared with those of radiative transfer model calculations using as inputs the acquired soil moisture and temperature data with appropriate values of dielectric constants for soil-water mixtures. A good agreement was found between the calculated and measured results. Similar calculations were made for the vegetated fields to estimate the effect of the vegetation covers.

Extensive data were collected on each of the plots to conduct daily water balance calculations and describe the soil water profile. The emphasis of the data collection activities was on the soil moisture. Soil moisture was determined by several methods and climatic data for determining rainfall input and evapotranspiration were collected.

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Precipitation and pan evaporation were determined on a daily basis. Soil moisture was measured at least twice a week and every time microwave measurements were made by NASA. The table below summarizes the soil moisture sampling for each plot.

Table 1
Soil moisture measurement program for each plot

	Number of Sample Sites	Depth (cm)
Gravimetric	6	0-2.5
		2.5-5
		5-15
Surface neutron	6	0-15
Two probe gamma	1	*
		3.8
		8.9
		14.0
		19.1
		24.1
		29.2
		34.3
		39.4
		47.0
		54.6
		62.2
		77.7
		92.7
		100.0

* This is the depth at which the source center was located. The effective measurement layer is about 1 cm to either side of the center; i.e. 3.8 cm measures from 2.5 to 5.0 cm.

Similar studies will be conducted for the 1980 growing season. The plot arrangement has been changed slightly. We anticipate collecting a complete data set for the entire growing season in 1980.

A series of aircraft experiments is being conducted over experimental watersheds monitored by USDA-SEA-AR. Ground observations of soil moisture, climatological and hydrologic variables are being collected in conjunction

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with remotely sensed aircraft data. Data collected previously in semiarid watersheds in Oklahoma and Texas were processed and a data report has been prepared (Jackson et al, 1980a). Although analyses are still underway, the results support the microwave results obtained in other investigations. Active microwave relationships between the backscattering coefficient and soil moisture were similar to those obtained at the University of Kansas (Jackson et al, 1980b).

Three additional experiments will be conducted at the Oklahoma site this year to obtain measurements under dry soil moisture conditions. During FY 81 data processing and analysis will be continued.

Aircraft experiments were conducted on watersheds located in humid areas of Florida and Georgia. Four flights were made in Florida and three in Georgia. The soils in these areas were sandier and the vegetation was more dense at these sites than encountered in other experiments. Data processing has been initiated. At the present time only the L and C band radiometer data have been prepared. Preliminary results show the expected trends and cause-effect relationships. The density of vegetation has a very distinct effect on the soil moisture-brightness temperature relationship.

During FY 81 the processing and analysis of the Florida-Georgia Data Set will be continued. No additional experiments are planned. Preliminary plans will be made in FY 81 to conduct a series of aircraft experiments designed specifically for hydrologic analysis. These will be conducted cooperatively by USDA, NASA and NOAA. The objective is to obtain remotely sensed data repetitively over a "hydrologically active" period of one or two months. The site selected would be one of interest to NOAA-NWS, in which their river forecast system is applied. This experiment would also serve the purposes of the next section on developing procedures for utilizing remotely sensed soil moisture observations and might provide information for the third area of research concerning the value of the information. It would also be related to the conservation and pollution project of AgRISTARS.

2. Development of Procedures for Utilizing Remotely Sensed Soil Moisture Data in Conventional Applications.

Regardless of the type of remotely sensed data used, all evidence indicates that at best these methods can provide an estimate of soil moisture within a shallow surface layer. However, if installed on a high altitude platform they can provide repetitive coverage over large areas. Since this type of data has never been available for application before, some implementation problems must be overcome.

Currently, two problems are under investigation. The first deals with how to utilize surface measurements in application that generally require soil moisture to a depth of one meter or more. A method for extrapolating surface soil moisture measurements has been developed and tested for bare soil conditions (Jackson, 1980). It is based upon the surface measurement, soil property information and soil physics relationships. The method worked fairly well in simulation tests for bare soils. Further research will be conducted during the next FY to extend this procedure to vegetated conditions and to evalute other approaches that utilize the repetative aspects of the data.

An investigation is also being conducted which will analyze the relationships of spatial variations of soil moisture and integrated areal measurements such as those which might be provided by poor resolution microwave radiometers at high altitudes. Data collected by various researchers over recent years was analyzed using geostatistical methods (Jackson and Schmugge, 1980). Results of the investigation showed that topography was the most important factor influencing soil moisture variability within otherwise homogeneous units. Investigations will be continued during FY 81 to better understand the cause and effect relationships and to incorporate a wider range of conditions.

3. Evaluation of the Worth of Soil Moisture Observations in Hydrology and Agriculture.

Repetitive measurements of soil moisture over large areas have been impractical in the past due to the alternatives available. With the development of remote sensing, data collection may be practical, however, it still needs to be ascertained if the information provided will be of enough value to make it cost-effective.

A series of simulation experiments were conducted using a hydrologic model and repetitive observations of soil moisture. The purpose of the experiment was to determine if the use of soil moisture observations would improve the simulations of watershed streamflow. If they did it would show the value of the information.

The USDA Hydrograph Laboratory Model of Watershed Hydrology was applied to four small watersheds in Oklahoma for which climatological, streamflow, and soil moisture data were available over an eight year period. Soil moisture was collected using a neutron probe at 6 inch increments every two or three weeks. Four sites were averaged for each watershed. These data were used as a surrogate for remotely sensed data.

Simulations were performed with and without soil moisture updates and streamflow estimates were compared to observed values. Generally, the use of the soil moisture observations to correct or update the model simulation of soil moisture improved the estimate of annual runoff. (Jackson, et al, 1980c).

Additional experiments are planned for FY 81 to test this concept using the NOAA-NWS River Forecast System Model which is more event oriented than the USDA model.

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APPENDIX C

PRESENTATION BY RICHARD NEWTON

TEXAS A&M UNIVERSITY

TAMU PRESENTATION MATERIAL FOR:

SOIL MOISTURE PROJECT
EVALUATION WORKSHOP
JUNE 16-17, 1980

TAMU APPROACH TO SOIL MOISTURE RELATED RESEARCH

ENERGY/SCENE INTERACTION

SOIL COMPLEX DIELECTRIC/MOISTURE RELATIONSHIP

MEASUREMENT MODEL INTERPRETATION

- SOIL MOISTURE PARAMETER
- DEPTH OF PARAMETER VALIDITY
- SCENE EFFECTS
  - SURFACE ROUGHNESS
  - VEGETATION
  - SOIL TEXTURE
  - CLIMATIC

TRUCK MEASUREMENTS

- L-, C-, X-BAND PASSIVE (CURRENT)
- L-, C-, X-BAND ACTIVE (PROPOSED)

SOIL WATER PROFILES

ANALYTICAL

- SOIL WATER PROFILE/SOIL TEMPERATURE PROFILE MODELS
  - SENSITIVITY STUDY TO PARAMETERS
  - EFFECT OF SPATIAL VARIABILITY
- SOIL WATER BUDGET MODELS
  - SPATIAL VARIABILITY STUDY

EMPIRICAL

- TWO FREQUENCY MICROWAVE APPROACH
  - SIMULATIONS
  - MEASUREMENT DEMONSTRATION

TAMU APPROACH (CONTINUED)

<u>AIRCRAFT EXPERIMENTS</u>

PASSIVE

- TRUCK RESULT VERIFICATION
- SOIL MOISTURE ESTIMATION TEST

ACTIVE

- TRUCK RESULT VERIFICATION
- SURFACE ROUGHNESS EFFECTS

<u>SATELLITE STUDIES</u>

ESMR

- SOIL MOISTURE/API MEASUREMENT
- CROP STRESS EARLY WARNING SYSTEM (PROPOSAL)

SEASAT

- SOIL MOISTURE LAND VERIFICATION EXPERIMENT

HCMM

- TEMPERATURE/CROP MOISTURE STRESS RELATIONSHIP

LANDSAT

- AQUIFER DRAWDOWN

NEW SYSTEM STUDIES

- PASSIVE

    RESOLUTION/ACCURACY TRADEOFF

    ESTIMATION ALGORITHM DEVELOPMENT

REVIEW OF SELECTED RESULTS

TRUCK MOUNTED RADIOMETER MEASUREMENT PROGRAM

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OBJECTIVES OF TRUCK MEASUREMENT PROGRAMS

- DETERMINE EFFECT OF PERMITTIVITY AND TEMPERATURE PROFILE SHAPE ON EMISSION
- DETERMINE EFFECT OF SURFACE ROUGHNESS (PERIODIC AND NON PERIODIC)
- DETERMINE MAXIMUM SENSING DEPTHS AS FUNCTION OF FREQUENCY
- DETERMINE VEGETATIOON PENETRATION CAPABILITY AS FUNCTION OF FREQUENCY
- DETERMINE A MEANINGFUL SOIL MOISTURE PARAMETER THAT CAN BE ESTIMATED FROM EMISSION MEASUREMENTS
- DEMONSTRATE THAT THE RELATIONSHIP BETWEEN SOIL PERMITTIVITY AND PRESSURE POTENTIAL IS INDEPENDENT OF SOIL TEXTURE

1974 TRUCK EXPERIMENT

Uniform Roughness
Bare and Vegetated
Irrigated

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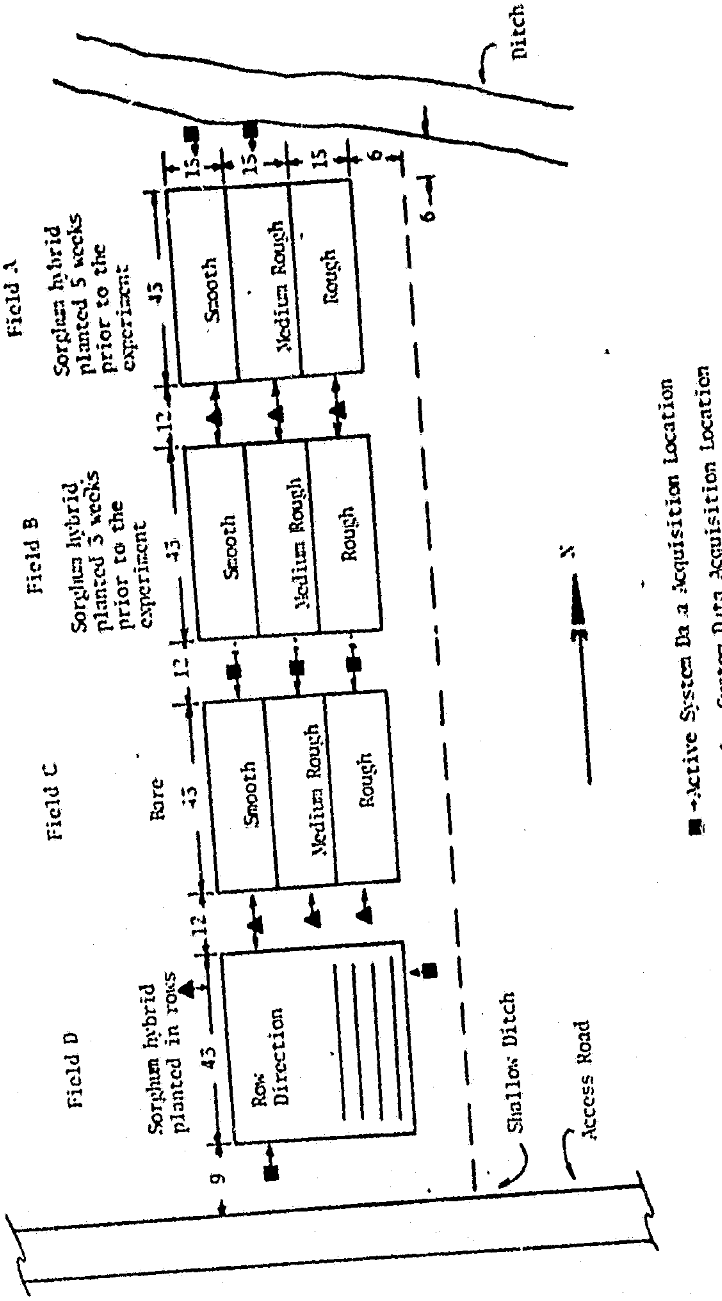

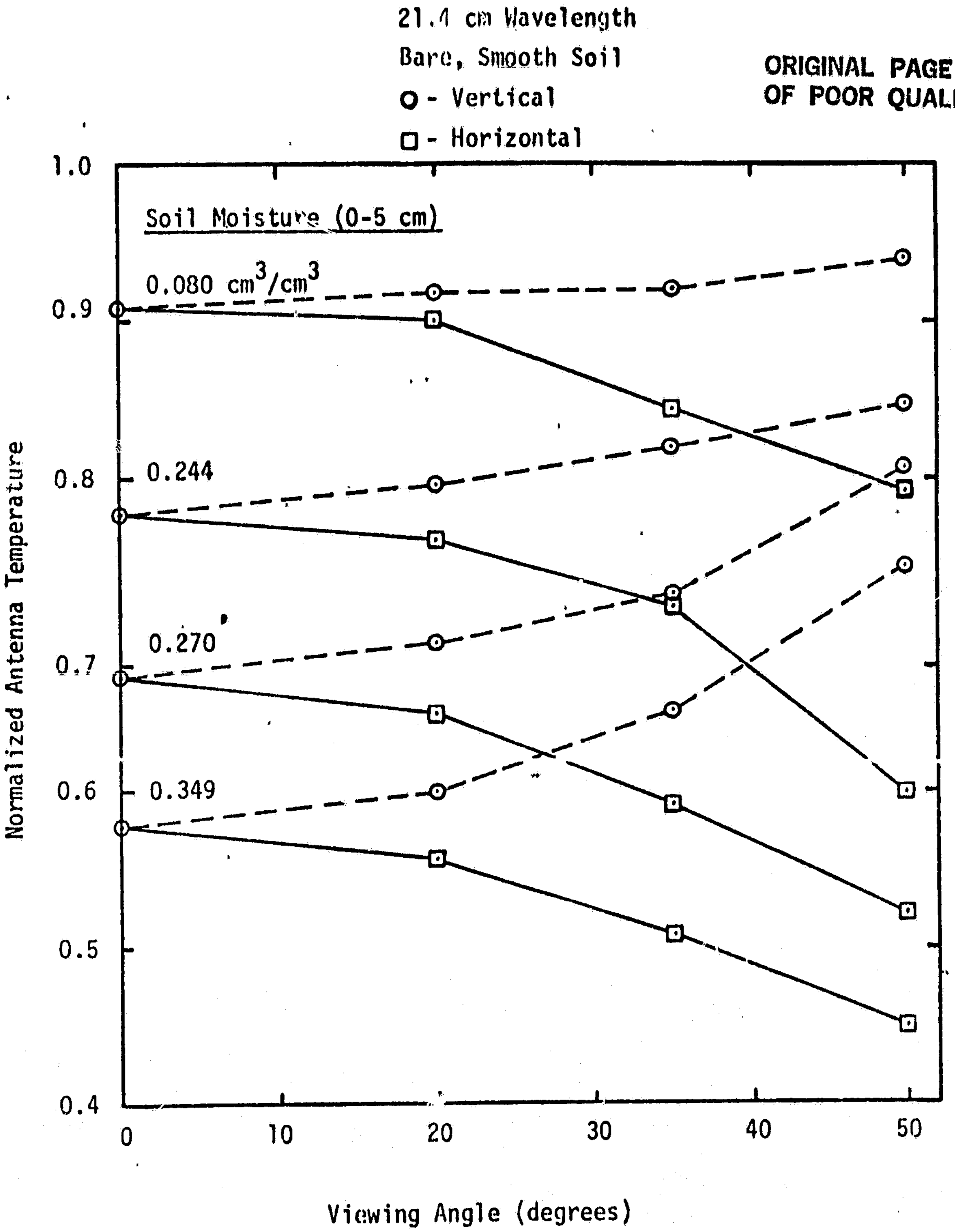

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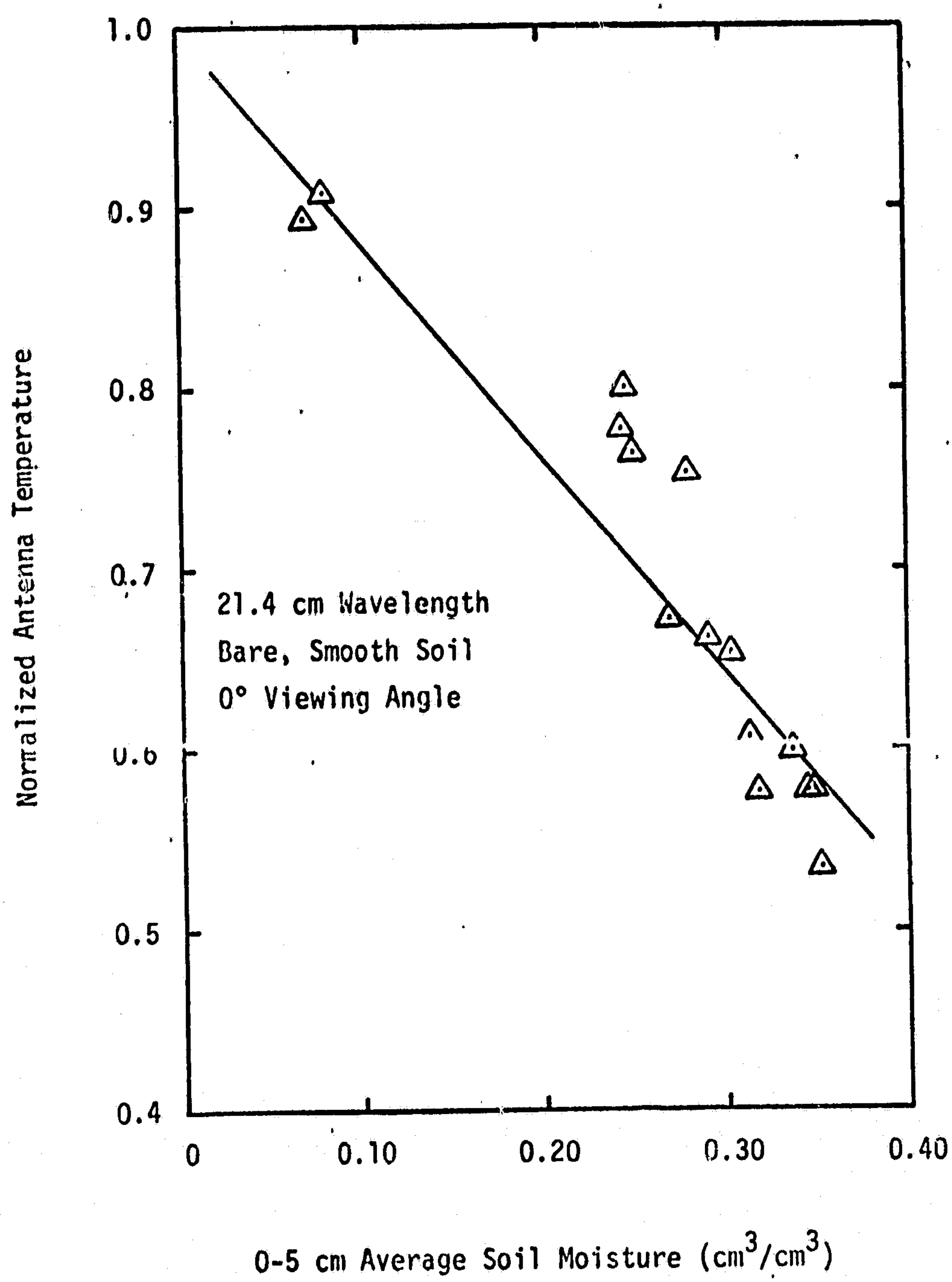

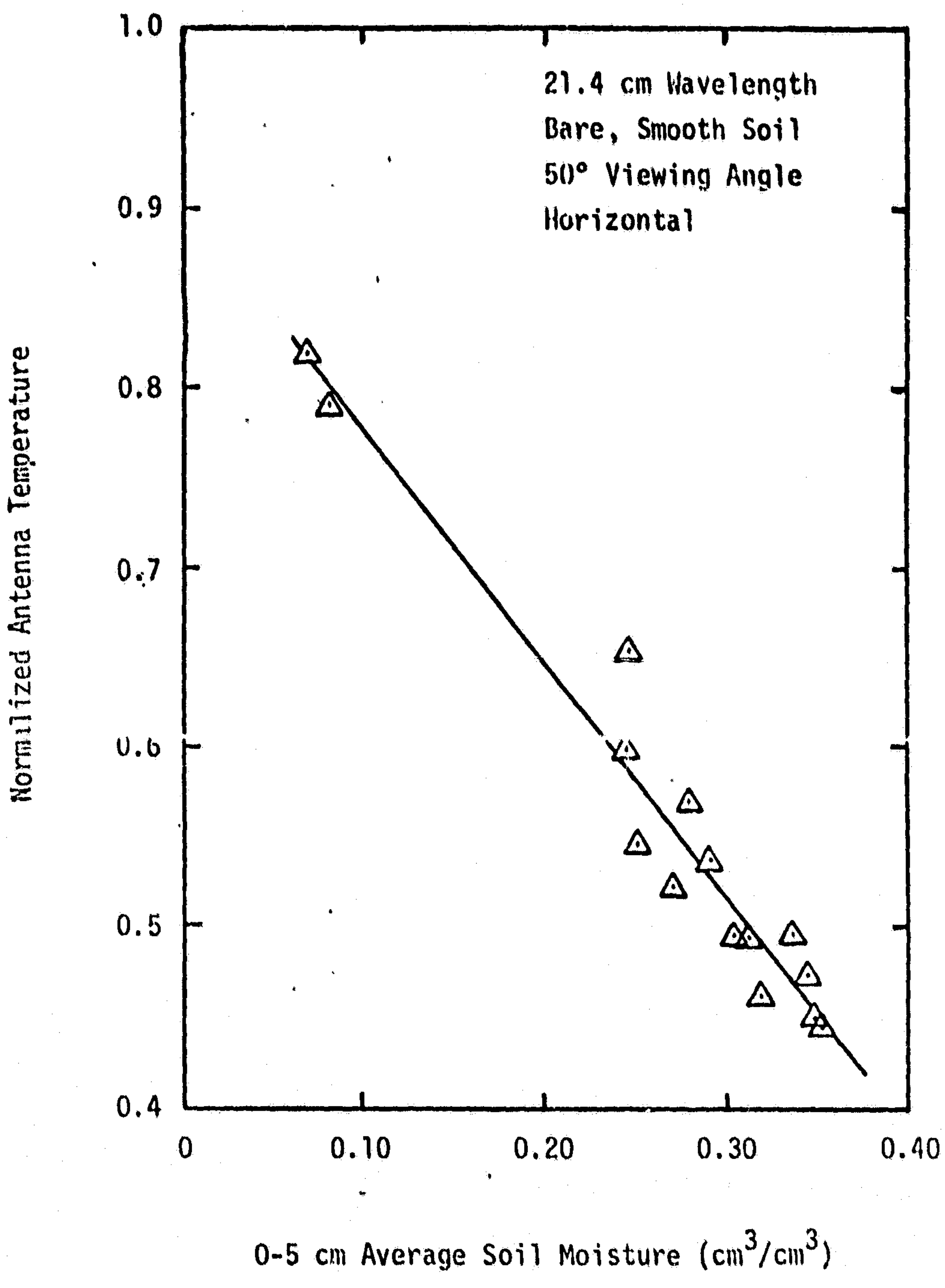
21.4 cm Wavelength
Bare, Smooth Soil
50° Viewing Angle
Horizontal
Normilized Antenna Temperature
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
0.10
0.20
0.30
0.40
0-5 cm Average Soil Moisture (cm3/cm3)

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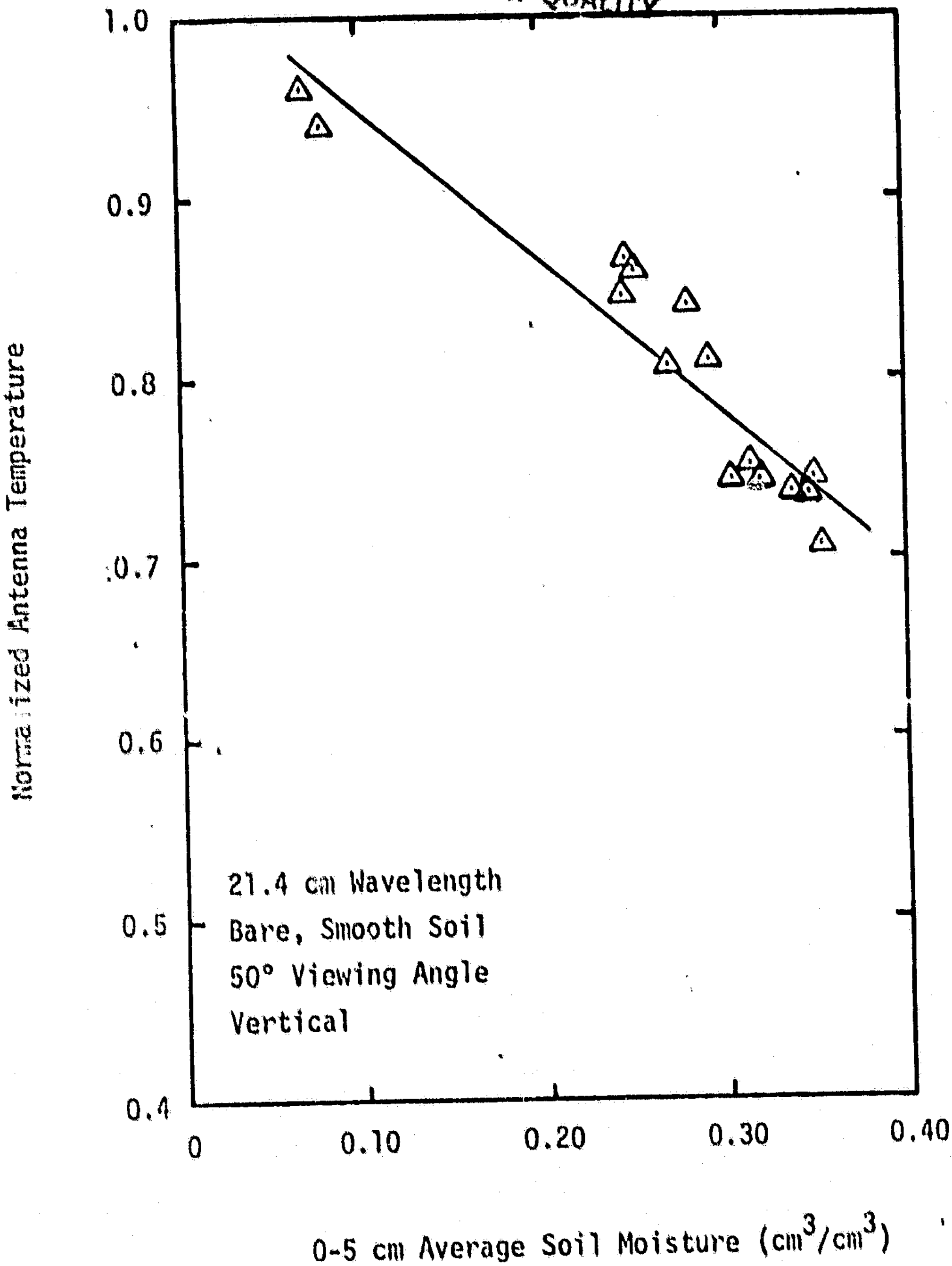

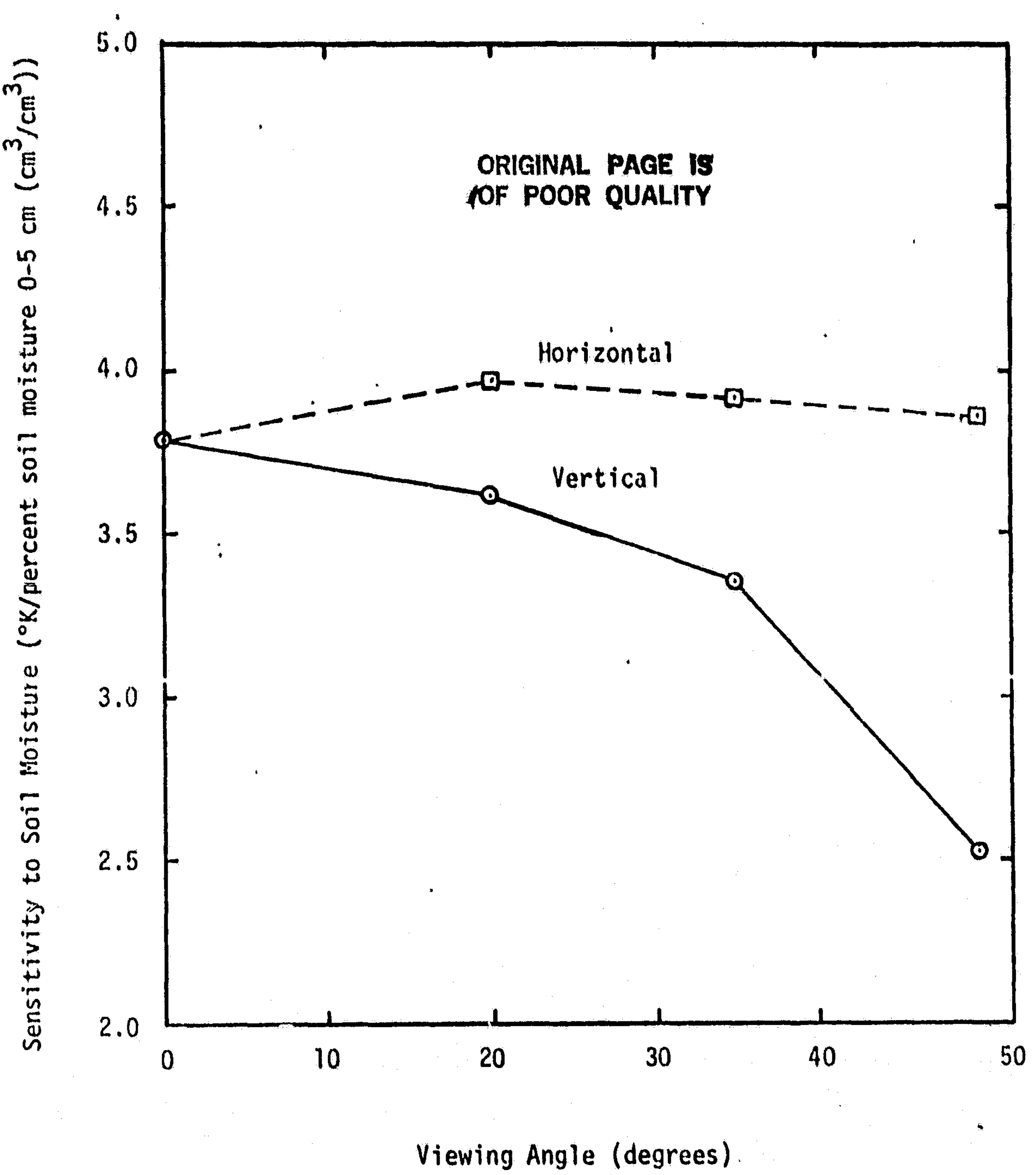
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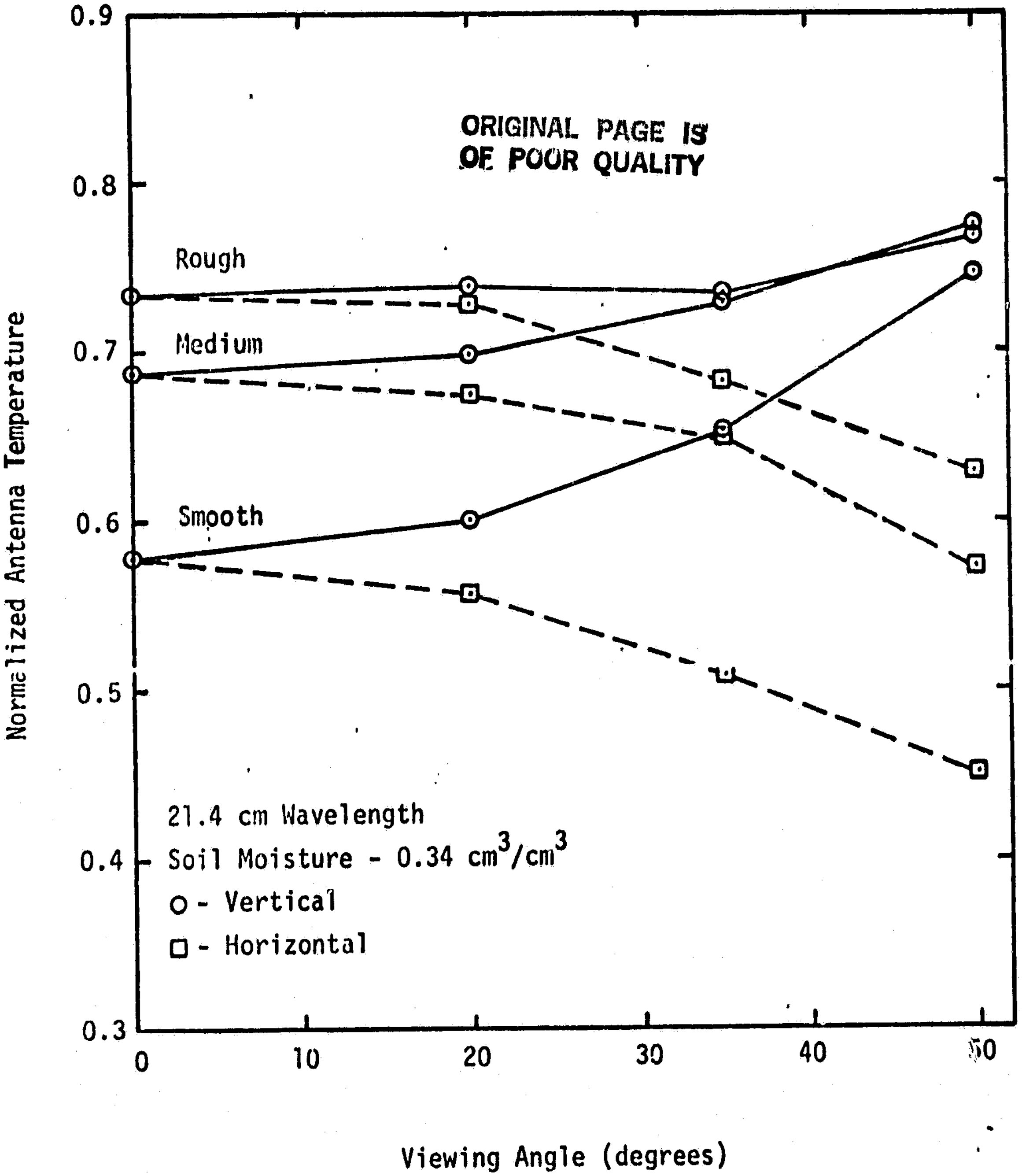
Horizontal
Vertical
5.0
4.5
4.0
3.5
3.0
2.5
2.0
0
10
20
30
40
50
Sensitivity to Soil Moisture (°K/percent soil moisture 0-5 cm (cm3/cm3))
Viewing Angle (degrees)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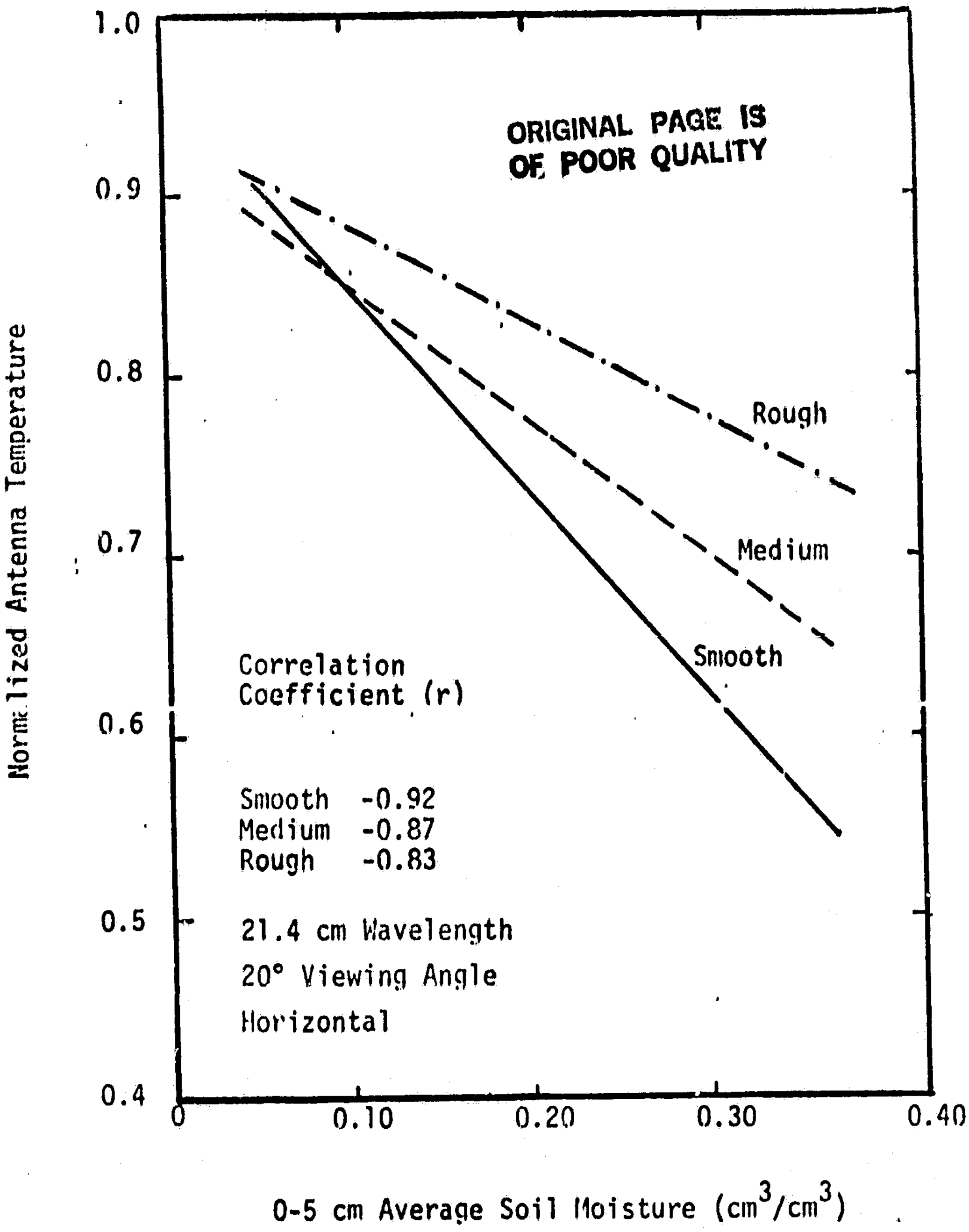
Rough
Medium
Smooth
21.4 cm Wavelength
Soil Moisture - 0.34 cm3/cm3
○ - Vertical
□ - Horizontal
Normalized Antenna Temperature
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
10
20
30
40
50
Viewing Angle (degrees)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Normalized Antenna Temperature
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
0.10
0.20
0.30
0.40
Rough
Medium
Smooth
Correlation
Coefficient (r)
Smooth -0.92
Medium -0.87
Rough -0.83
21.4 cm Wavelength
20° Viewing Angle
Horizontal
0-5 cm Average Soil Moisture (cm3/cm3)

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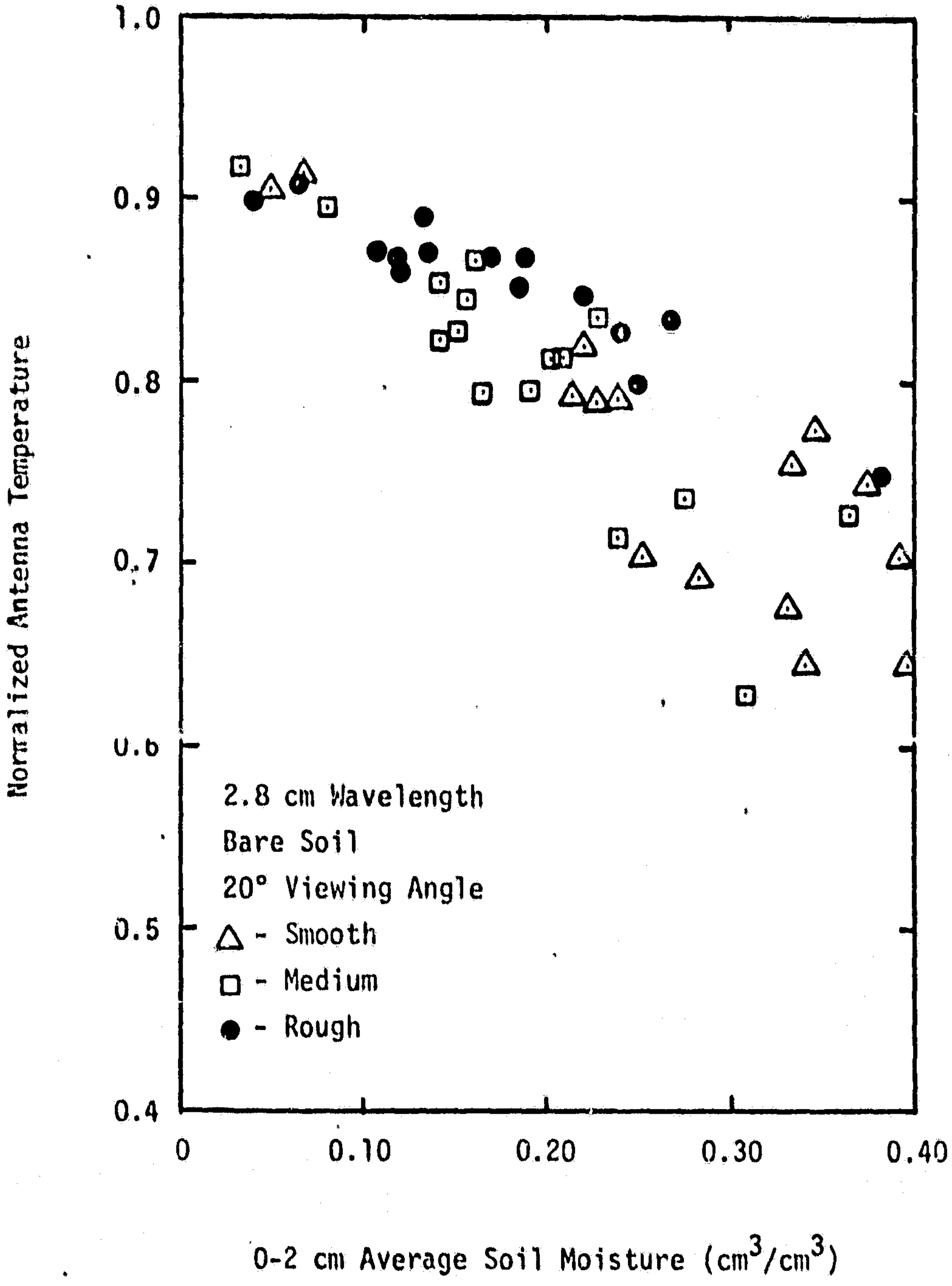

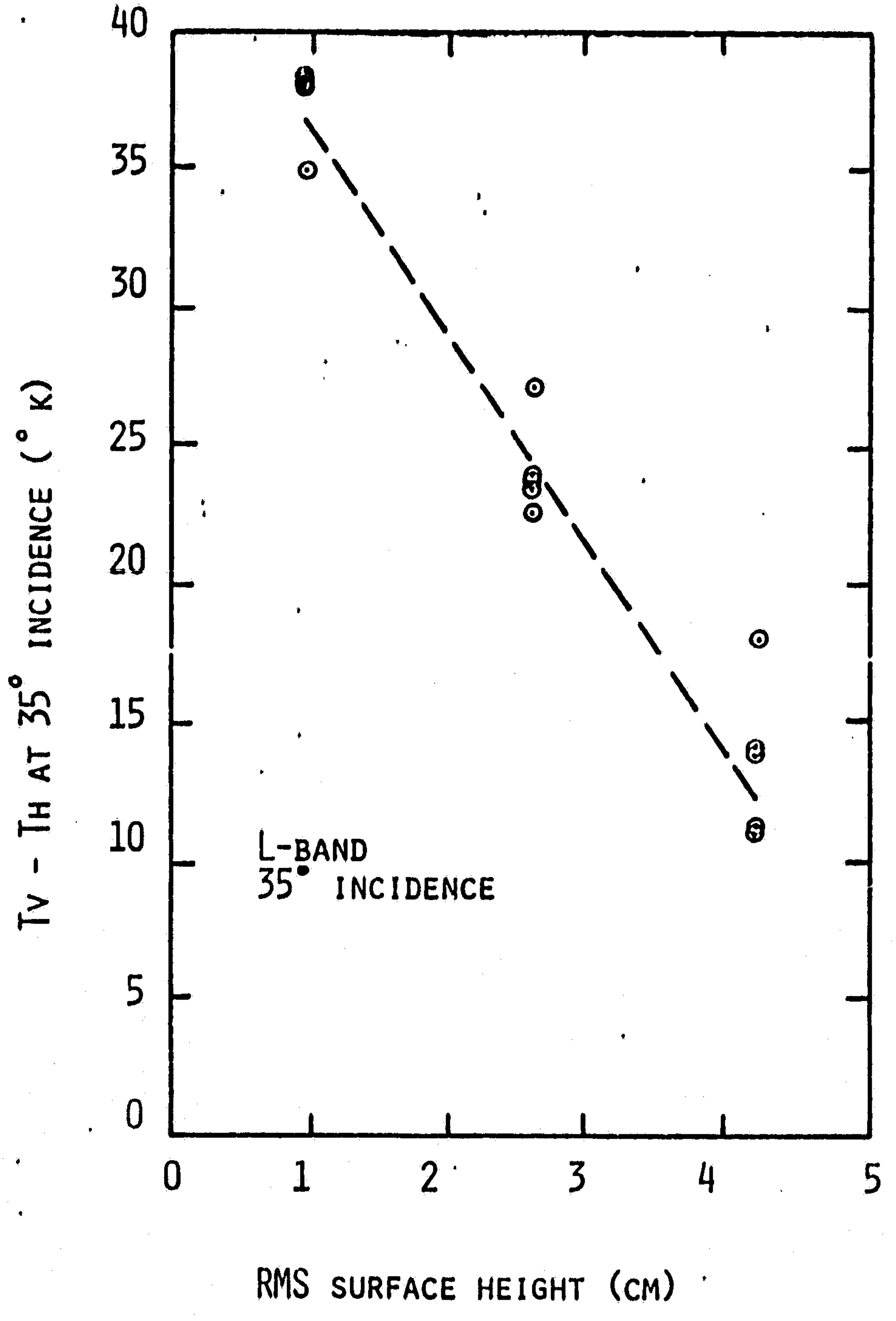
40
35
30
25
20
15
10
5
0
TV - TH AT 35° INCIDENCE (° K)
L-BAND
35° INCIDENCE
0
1
2
3
4
5
RMS SURFACE HEIGHT (CM)

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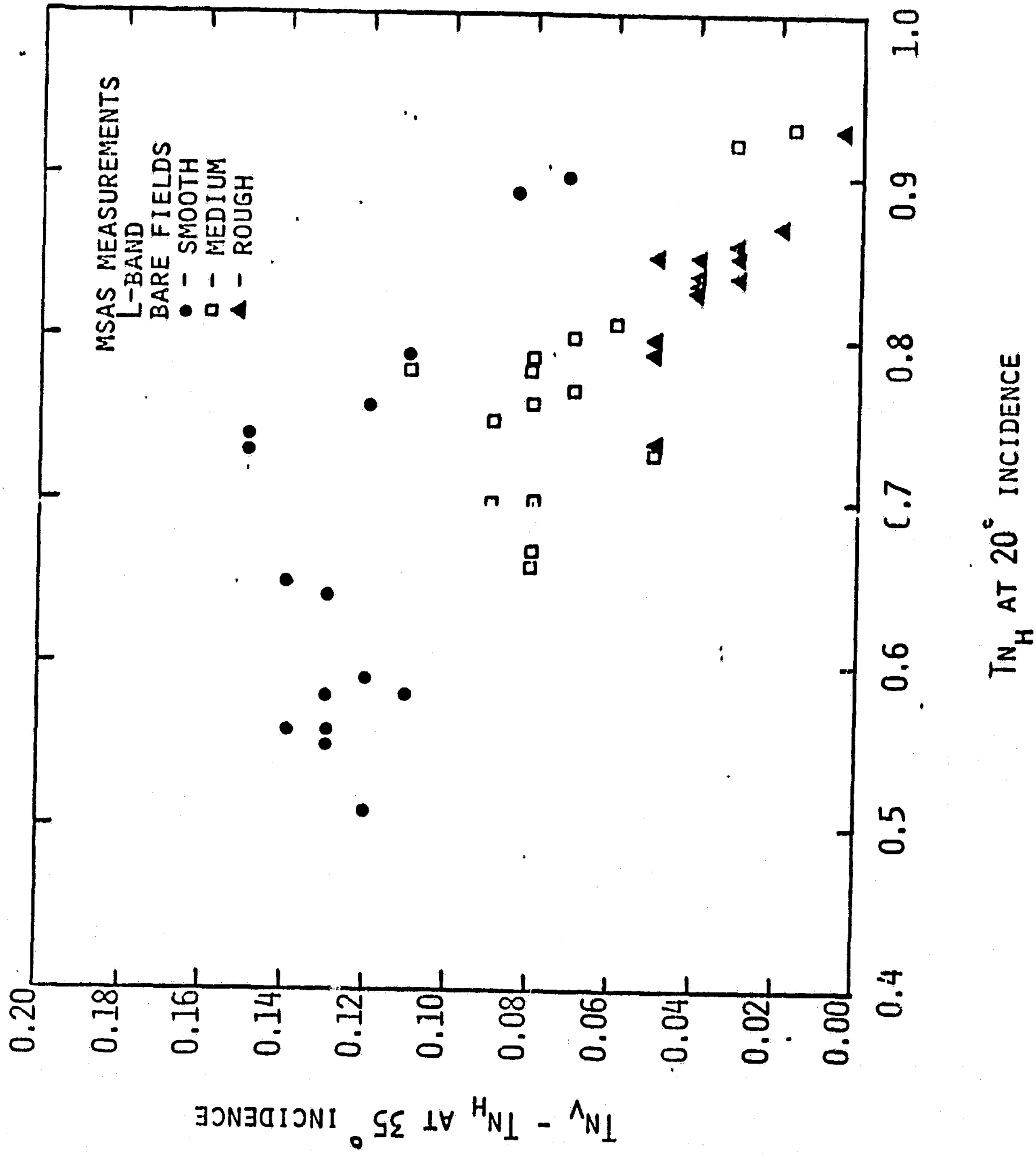

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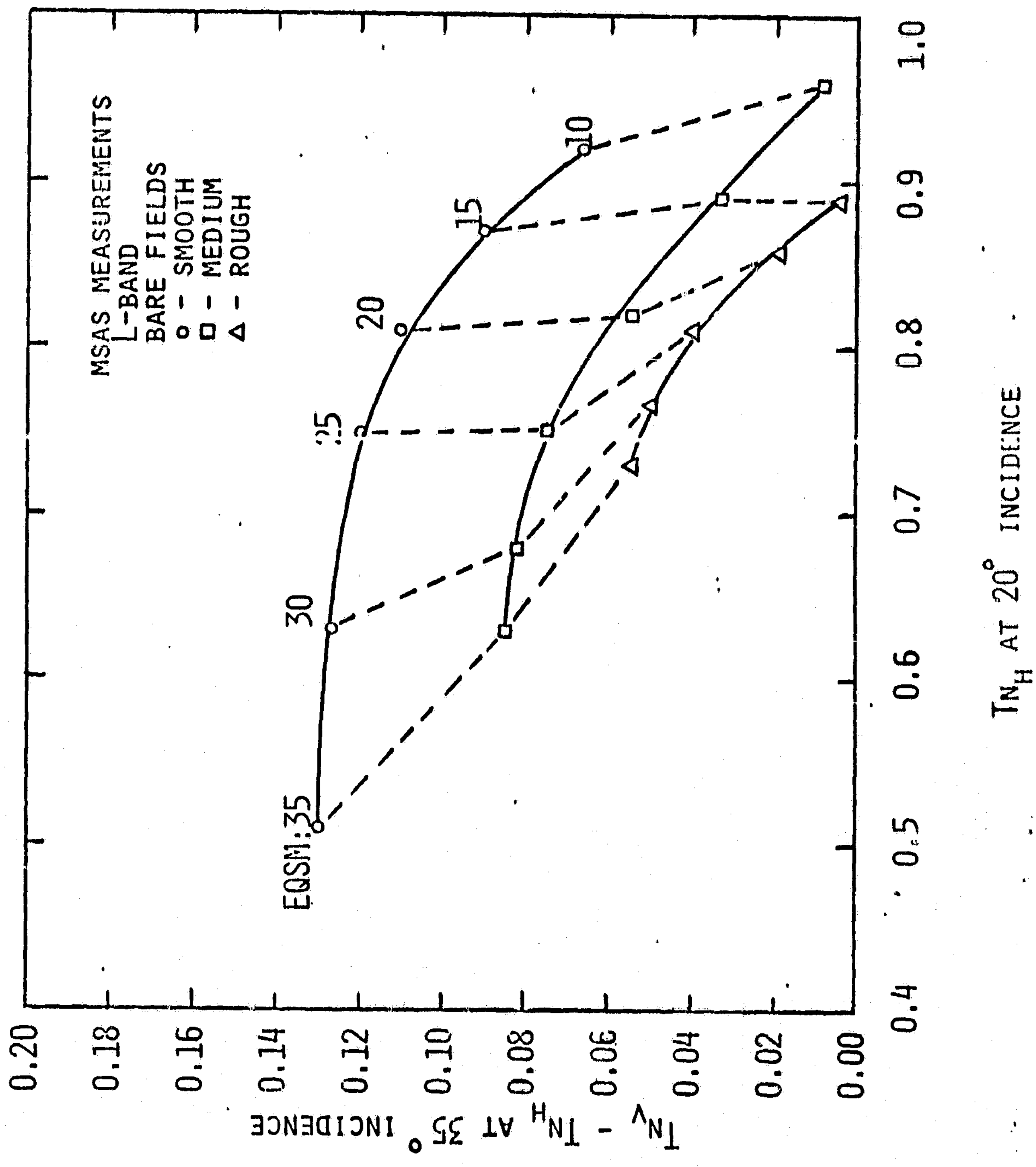

1975 TRUCK EXPERIMENT

Row Tillage

Bare and Vegetated

Irrigated

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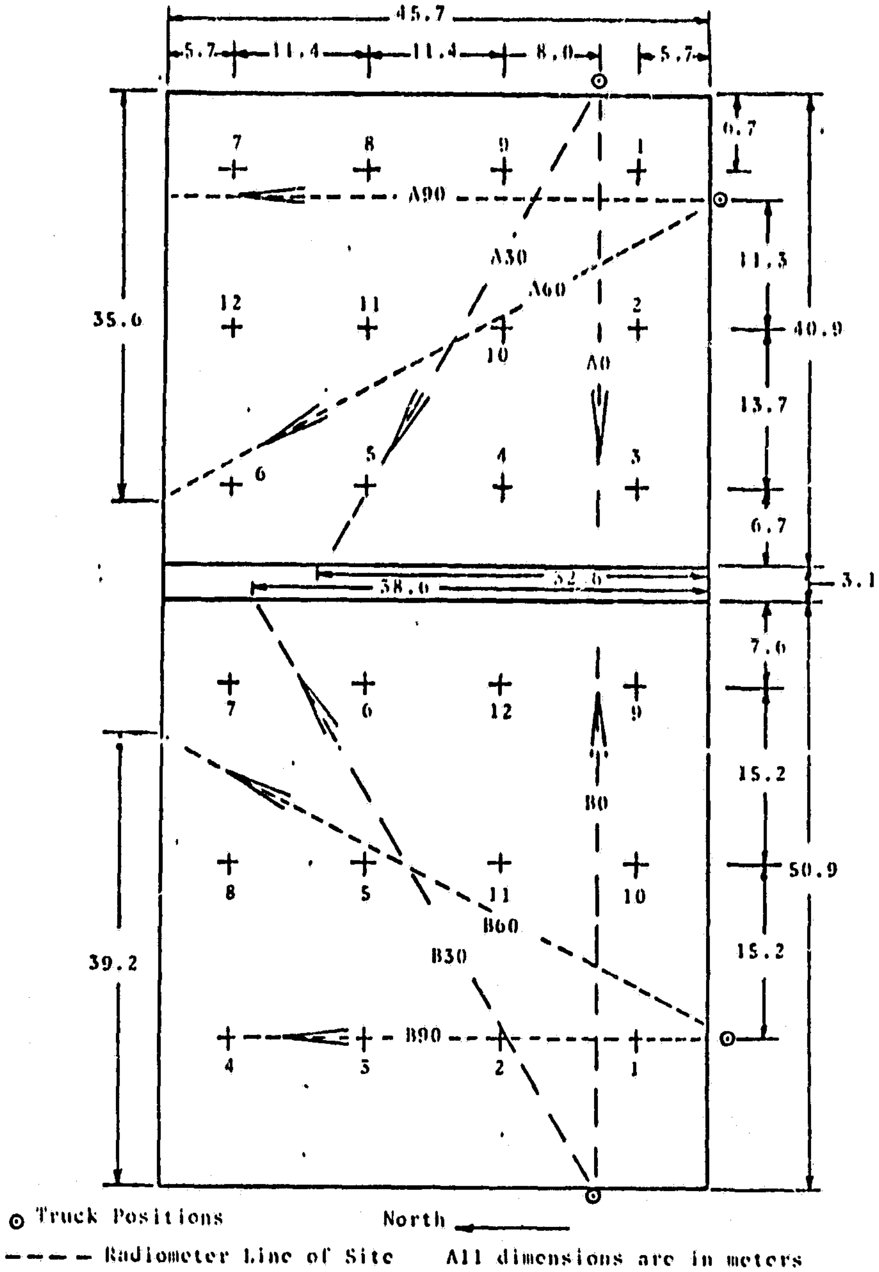
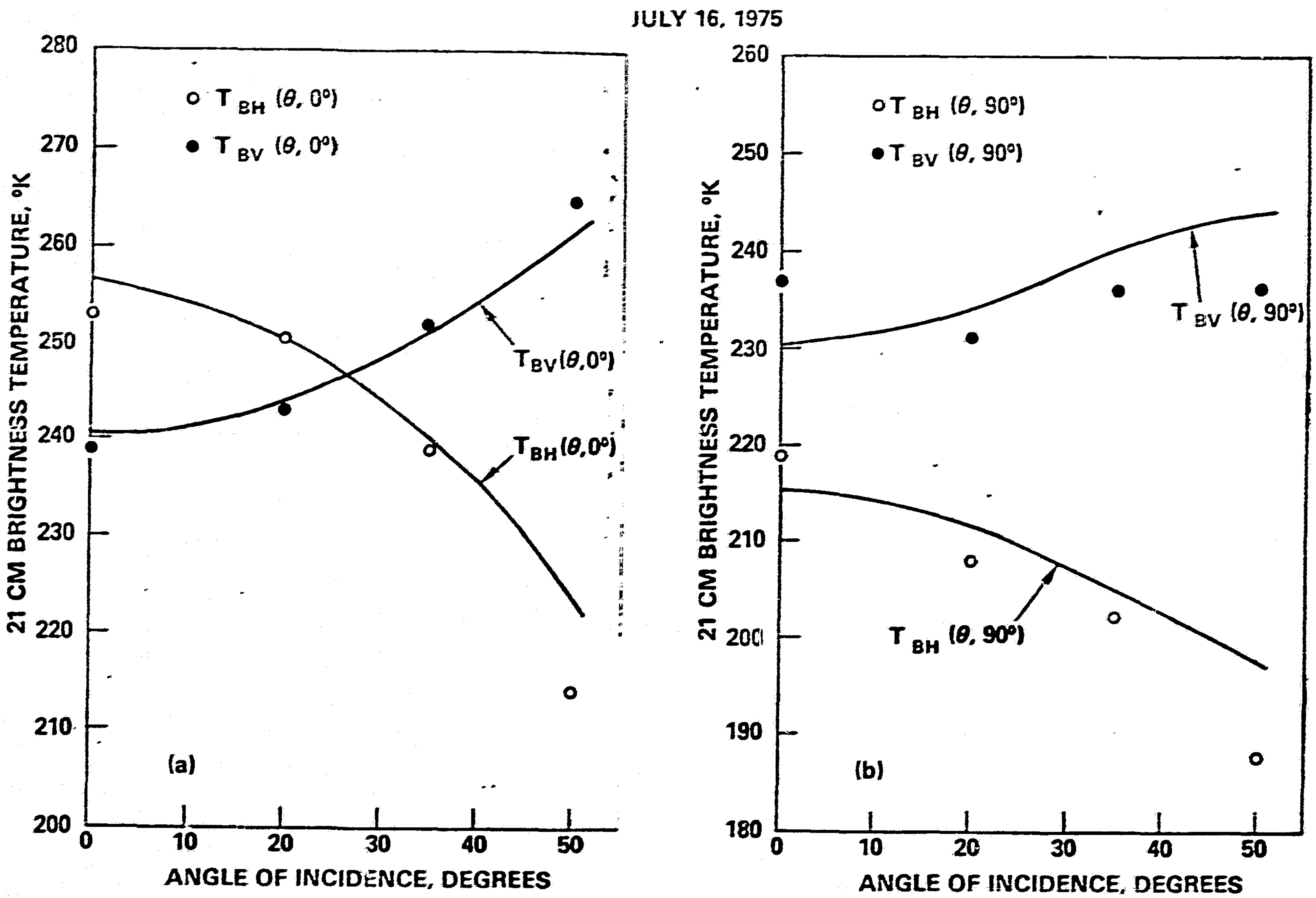
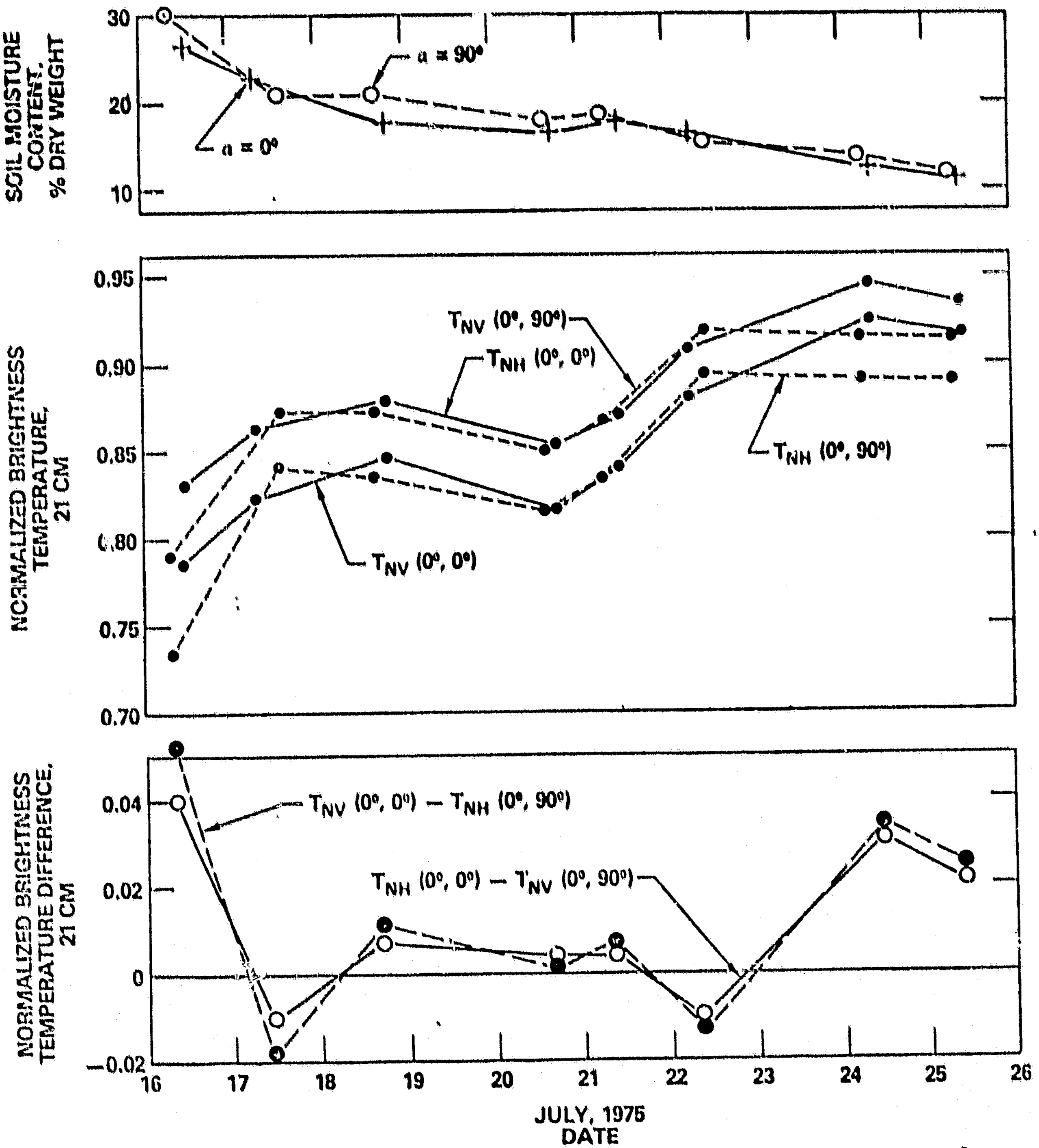


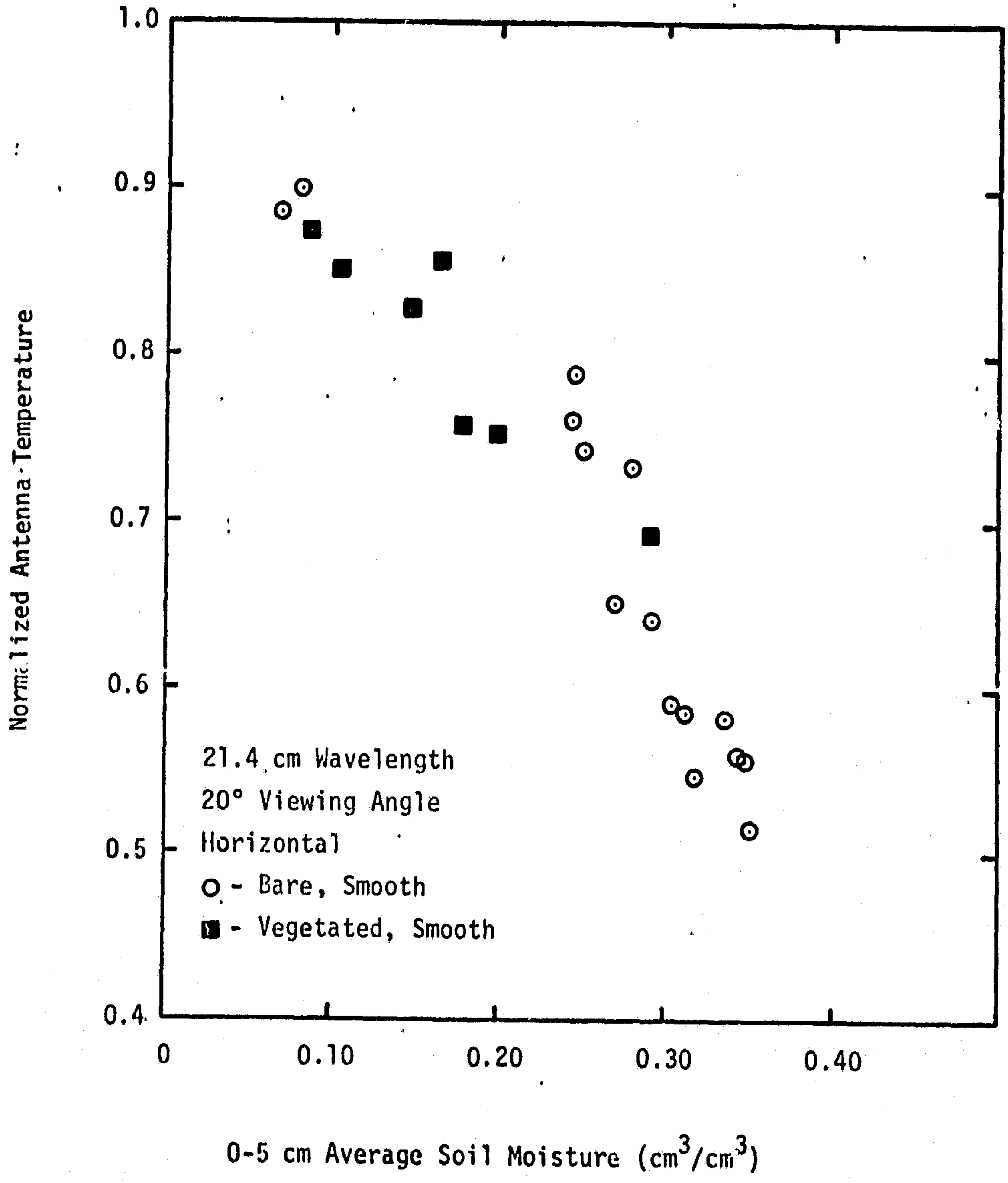


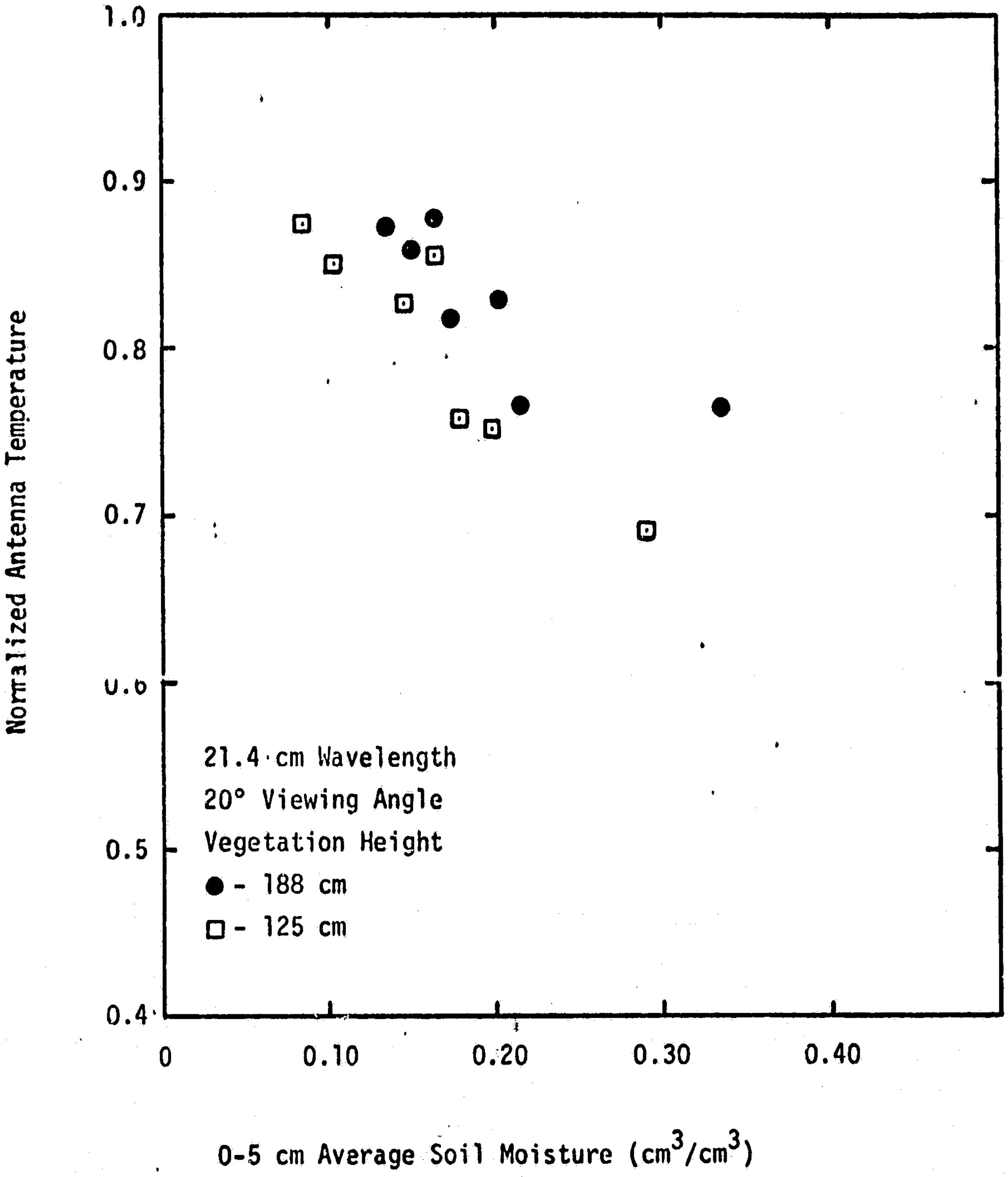
A comparison of the measured and calcul: ted brightness temperatures as a function of incident angle for measurements on July 16, 1975. (a): $a = 0°$, (b): $a = 90°$.



The time history of the soil moisture content, normalized brightness temperatures and their differences for the entire radiometric measurements in July 1975.

EFFECTS OF VEGETATION


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
0.10
0.20
0.30
0.40
Normalized Antenna-Temperature
0-5 cm Average Soil Moisture (cm3/cm3)
21.4 cm Wavelength
20° Viewing Angle
Horizontal
O - Bare, Smooth
■ - Vegetated, Smooth


Normalized Antenna Temperature
1.0
0.9
0.8
0.7
0.6
0.5
0.4
21.4 cm Wavelength
20° Viewing Angle
Vegetation Height
● - 188 cm
□ - 125 cm
0
0.10
0.20
0.30
0.40
0-5 cm Average Soil Moisture (cm3/cm3)

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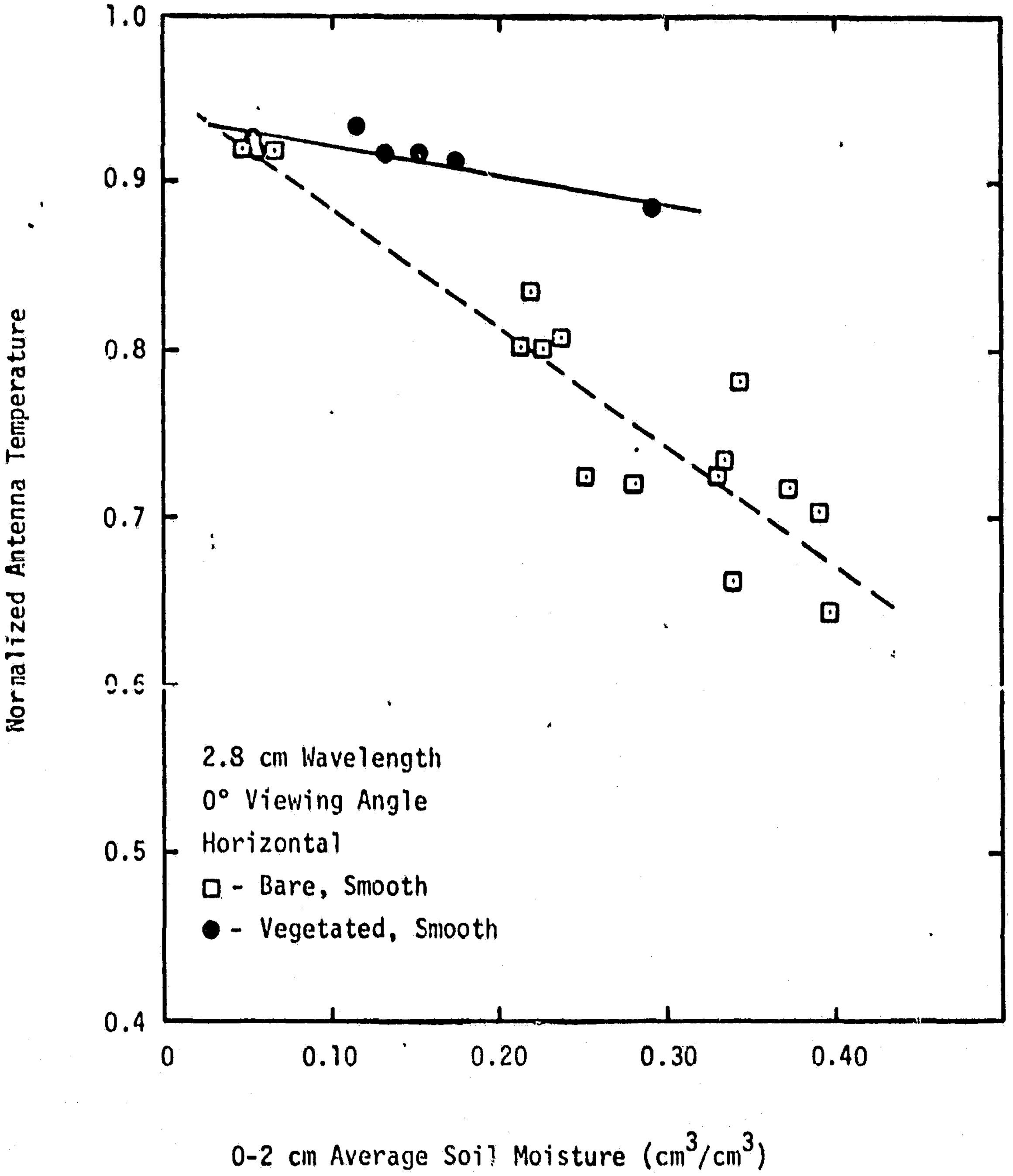

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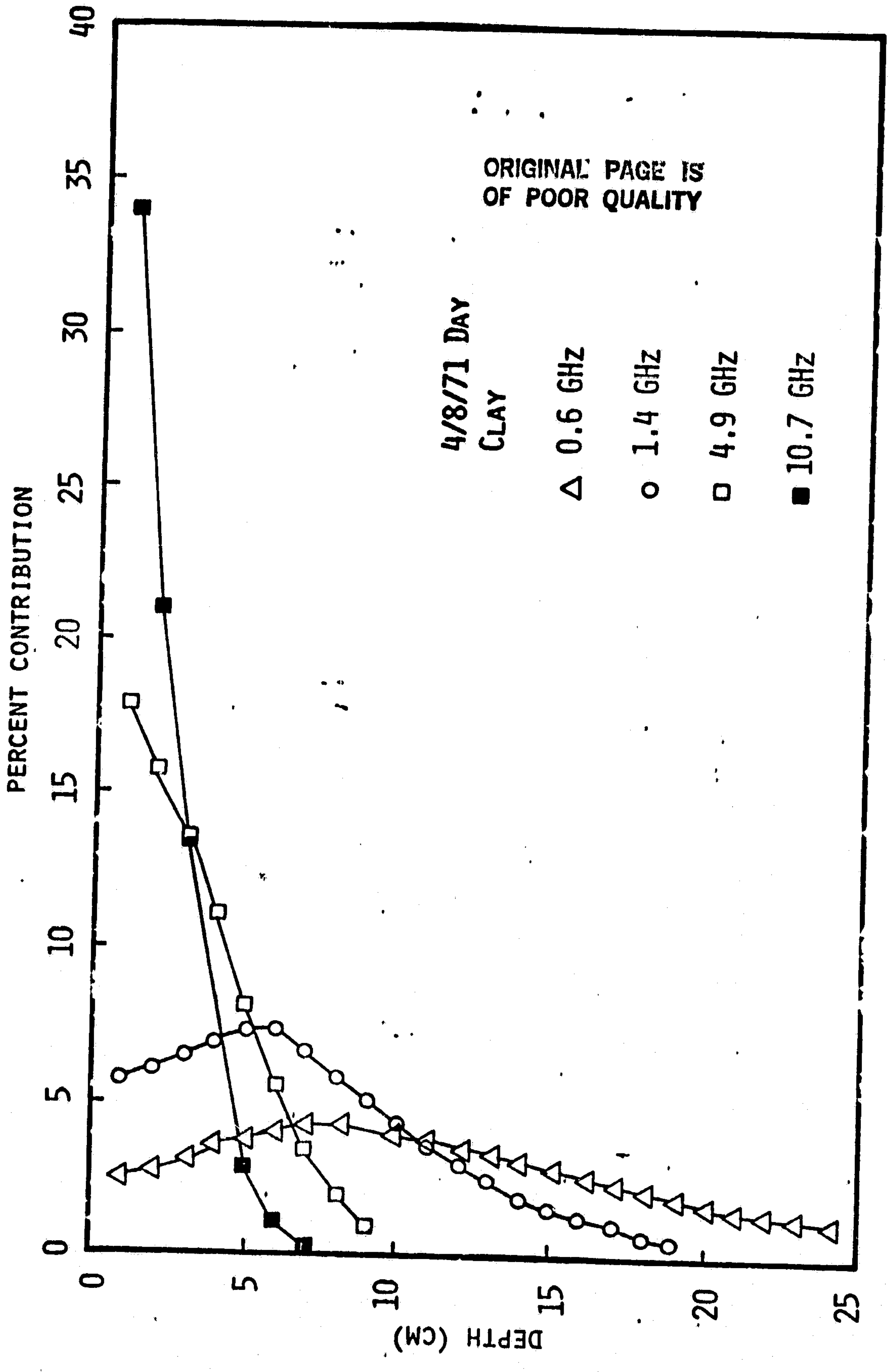
OBJECTIVES OF AIRCRAFT MEASUREMENTS PROGRAMS

- Verify Results of Controlled Truck Experiments Over Realistic Field Conditons
- Demonstrate Ability to Estimate a Moisture Parameter from a Radiometer Measurement
- Document Degradation Due to Vegetatioon and Roughness

Major Problems

- Inability to Adequately Ground Truth Test Area
- Inadequate Soil Moisture Variations Over Test Area
- Non-Uniformity Over Test Fields
- Small Number of Bare Fields


PERCENT CONTRIBUTION
0
5
10
15
20
25
30
35
40
DEPTH (CM)
0
5
10
15
20
25
4/8/71 DAY
CLAY
△ 0.6 GHz
○ 1.4 GHz
□ 4.9 GHz
■ 10.7 GHz
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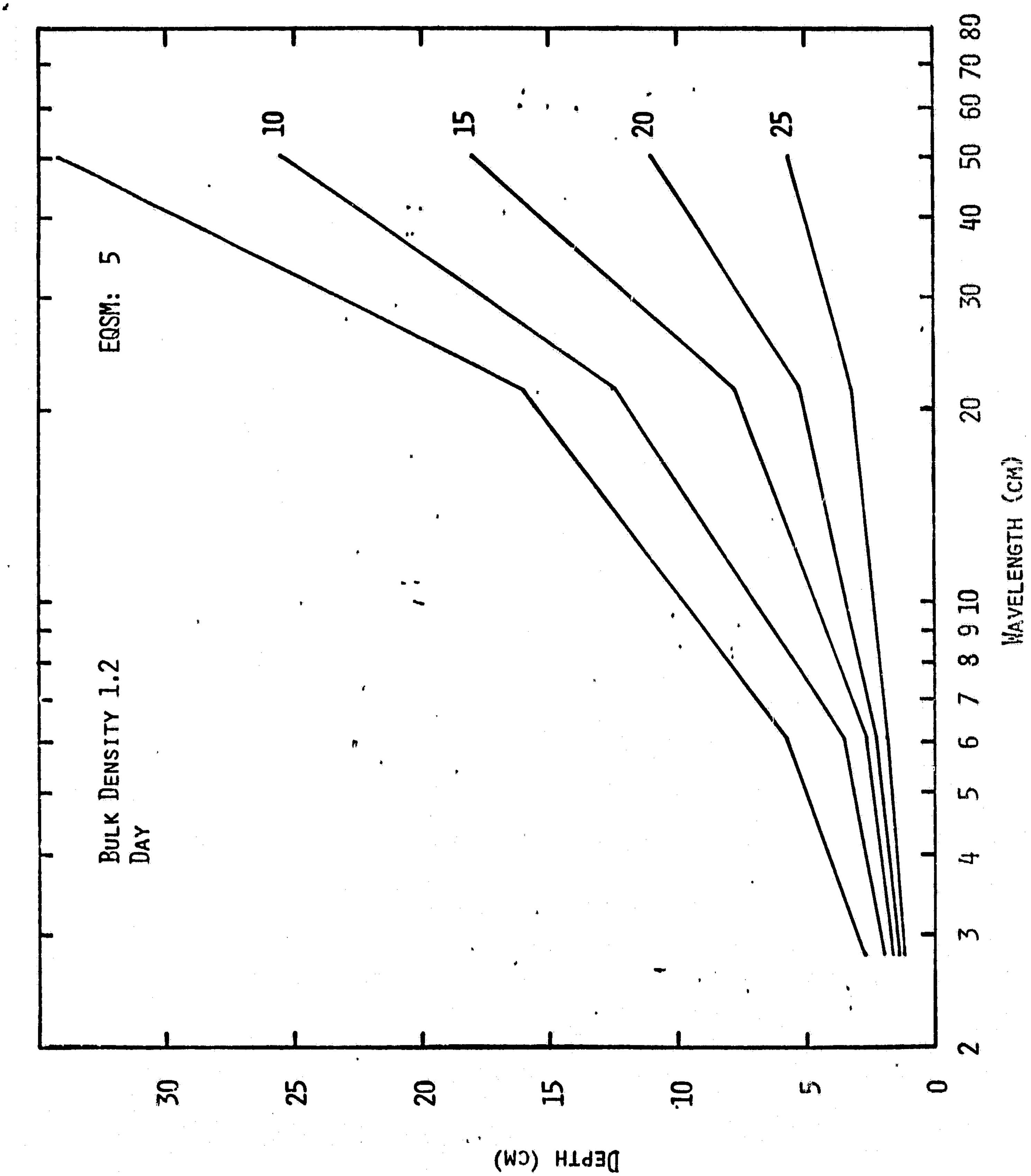
Bulk Density 1.2
Day
EQSM: 5
10
15
20
25
Depth (cm)
0
5
10
15
20
25
30
Wavelength (cm)
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80

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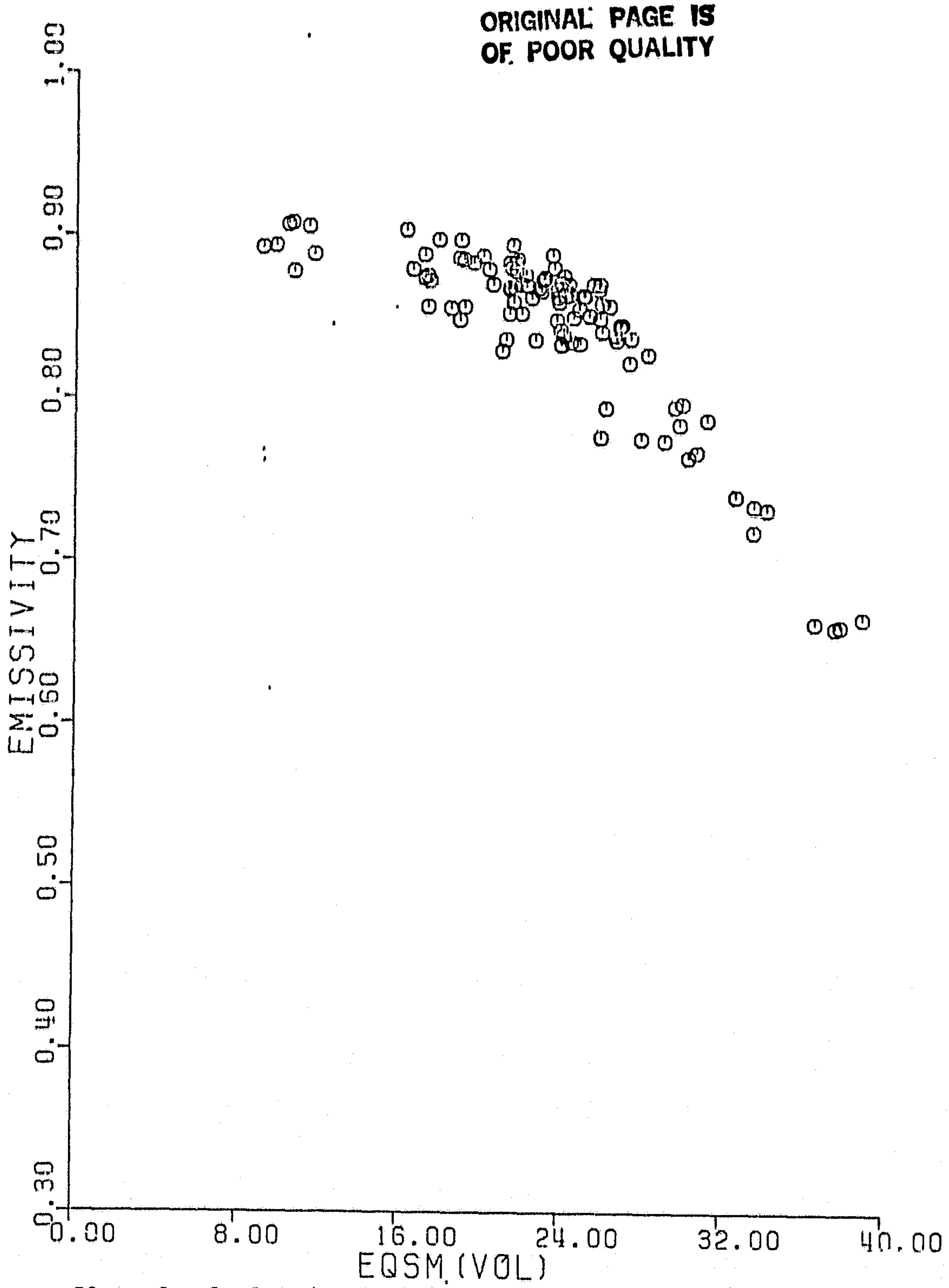
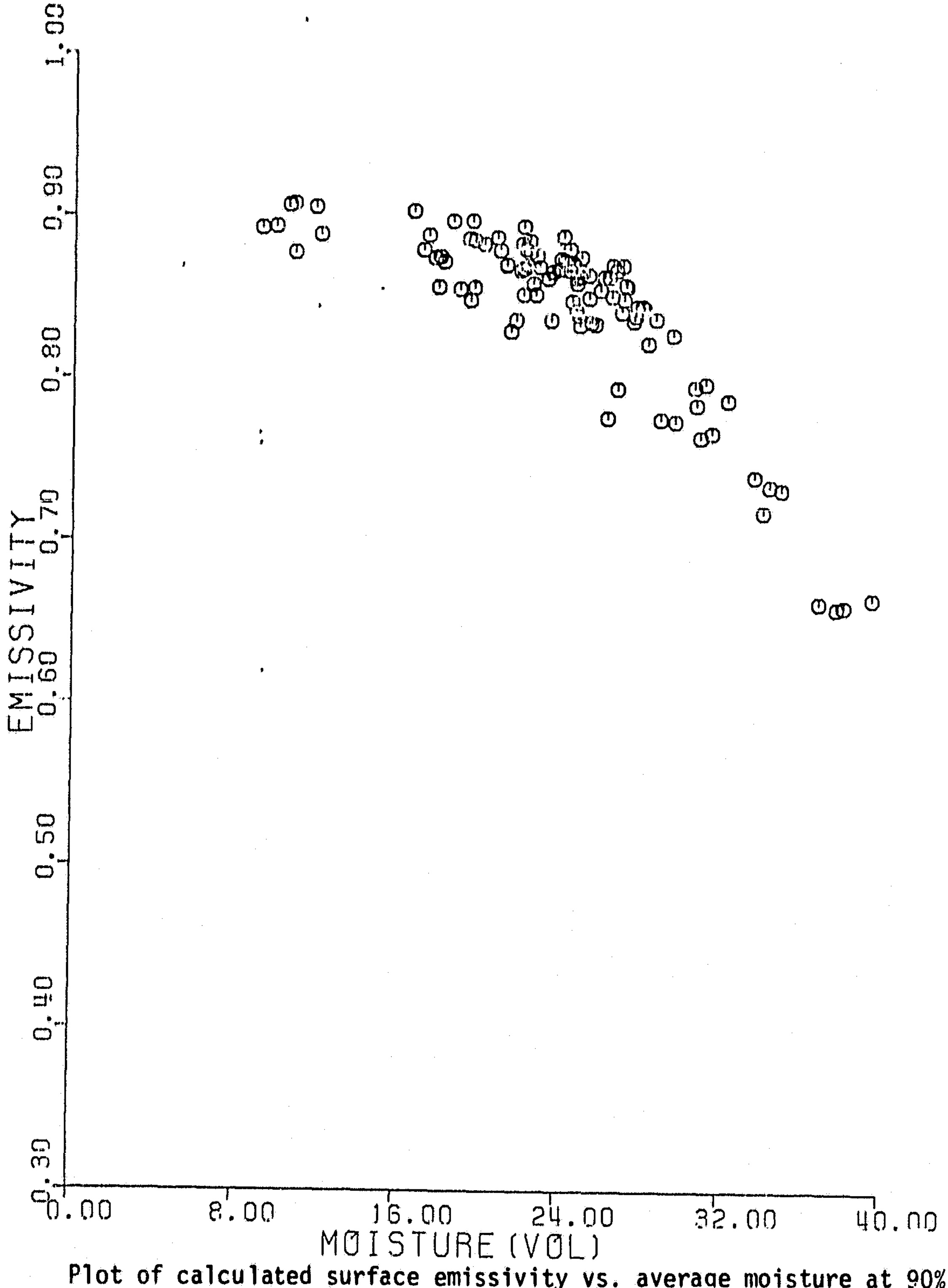


Plot of calculated emissivity vs. equivalent soil moisture for clay soil. (Phoenix, 1975, bare fields).



Plot of calculated surface emissivity vs. average moisture at 90% radiative contribution depth for clay soil. (Phoenix, 1975, bare fields).

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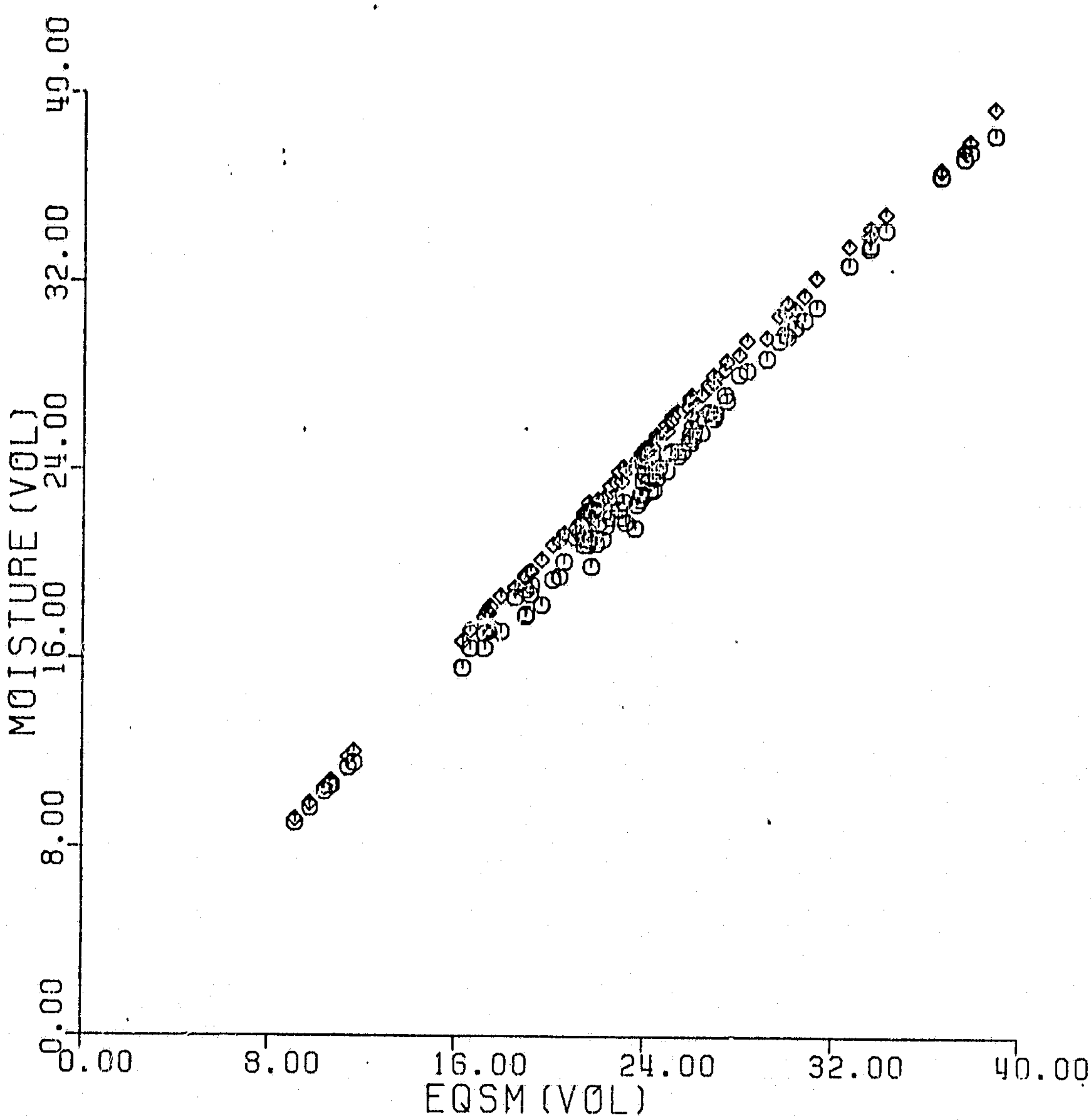
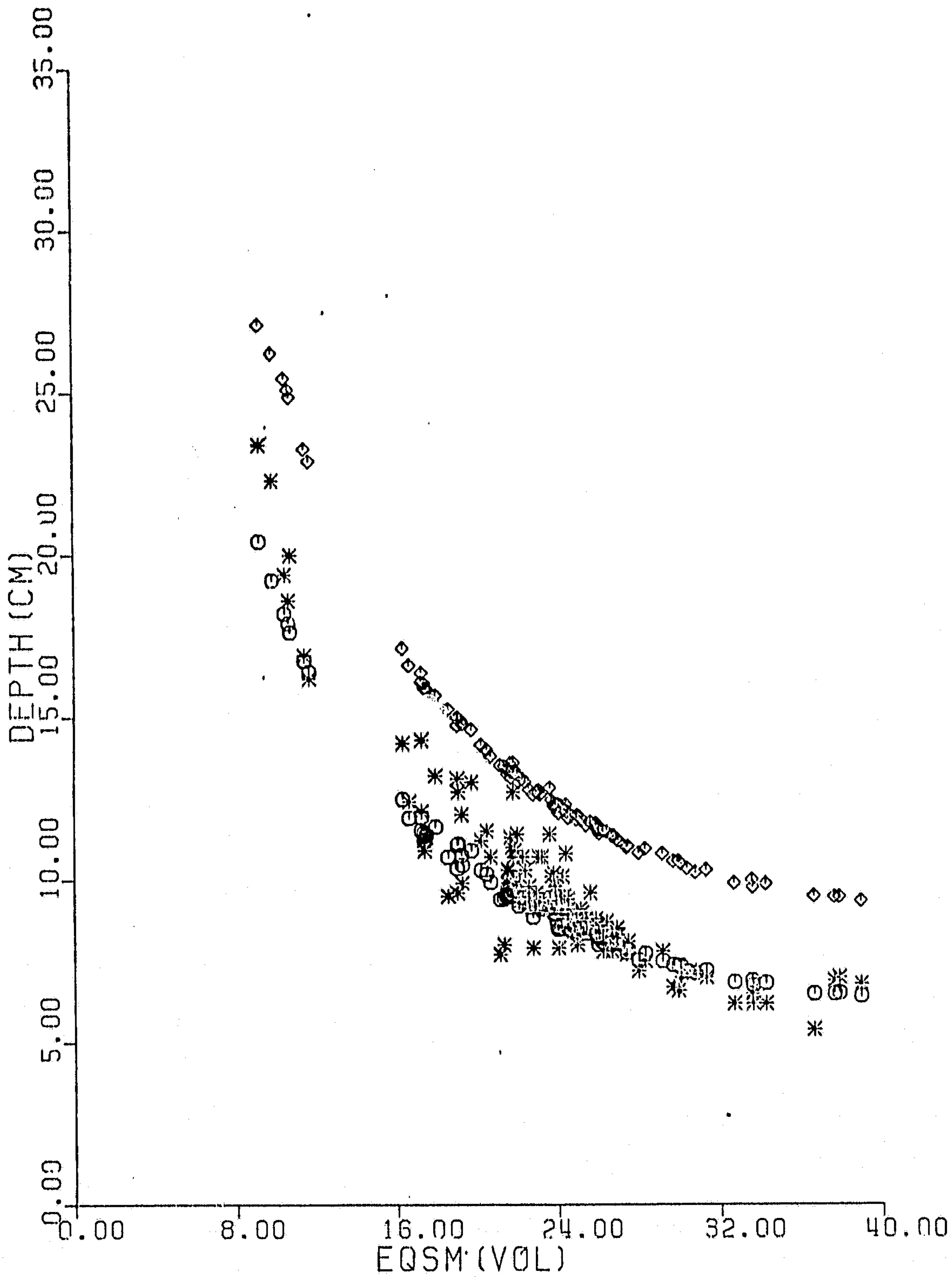


Plot of average moisture content at 80% and 90% radiative contribution depths vs. equivalent soil moisture for clay soil. (Phoenix, 1975, bare fields).



Plot of EQSM sampling depth, 80% and 90% radiative contribution depths vs. equivalent soil moisture for clay soil. (Phoenix, 1975, bare fields).

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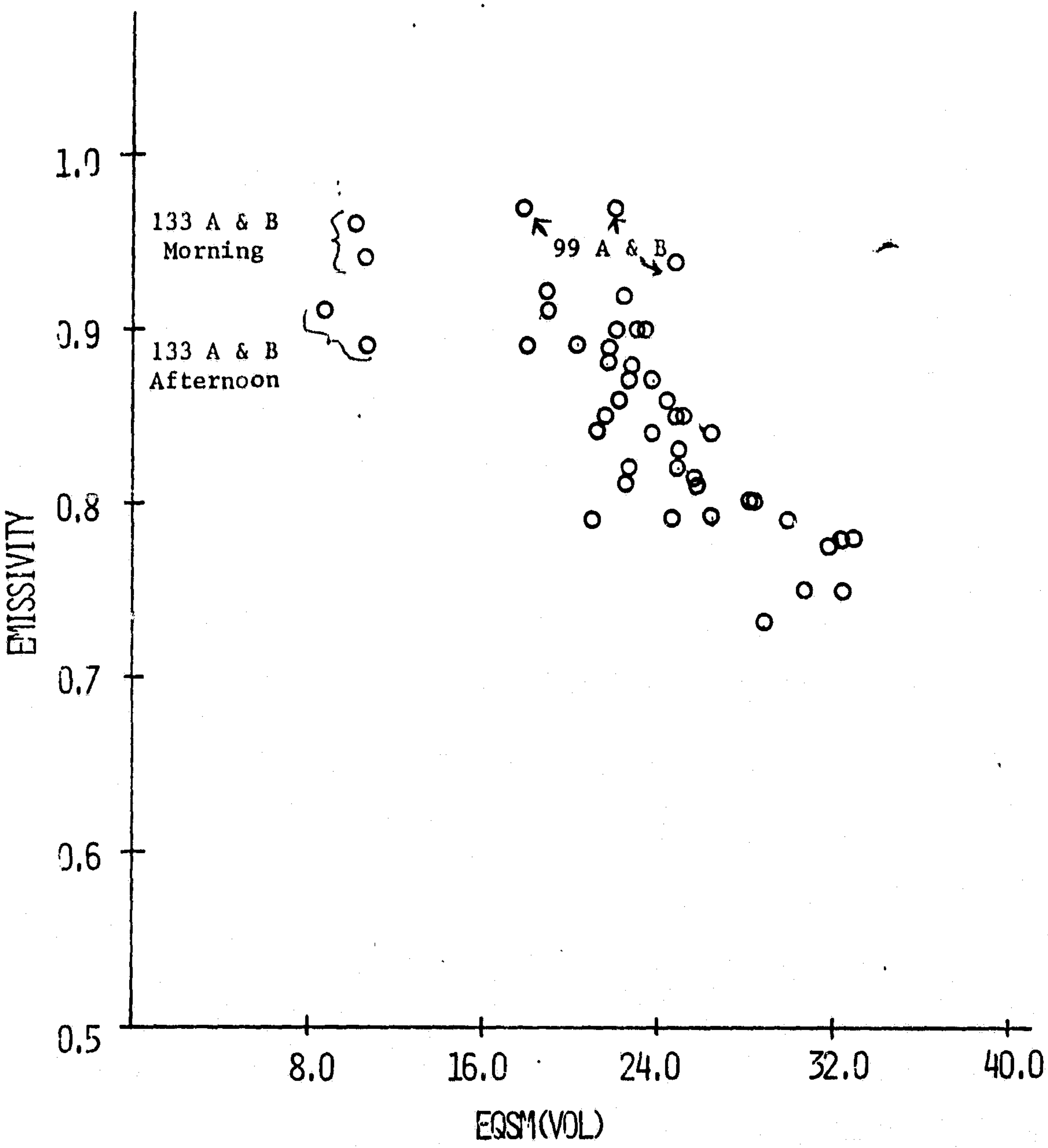

Plot of measured emissivity(L-Band,0°) vs. equivalent soil moisture (Phoenix,1975,bare fields).

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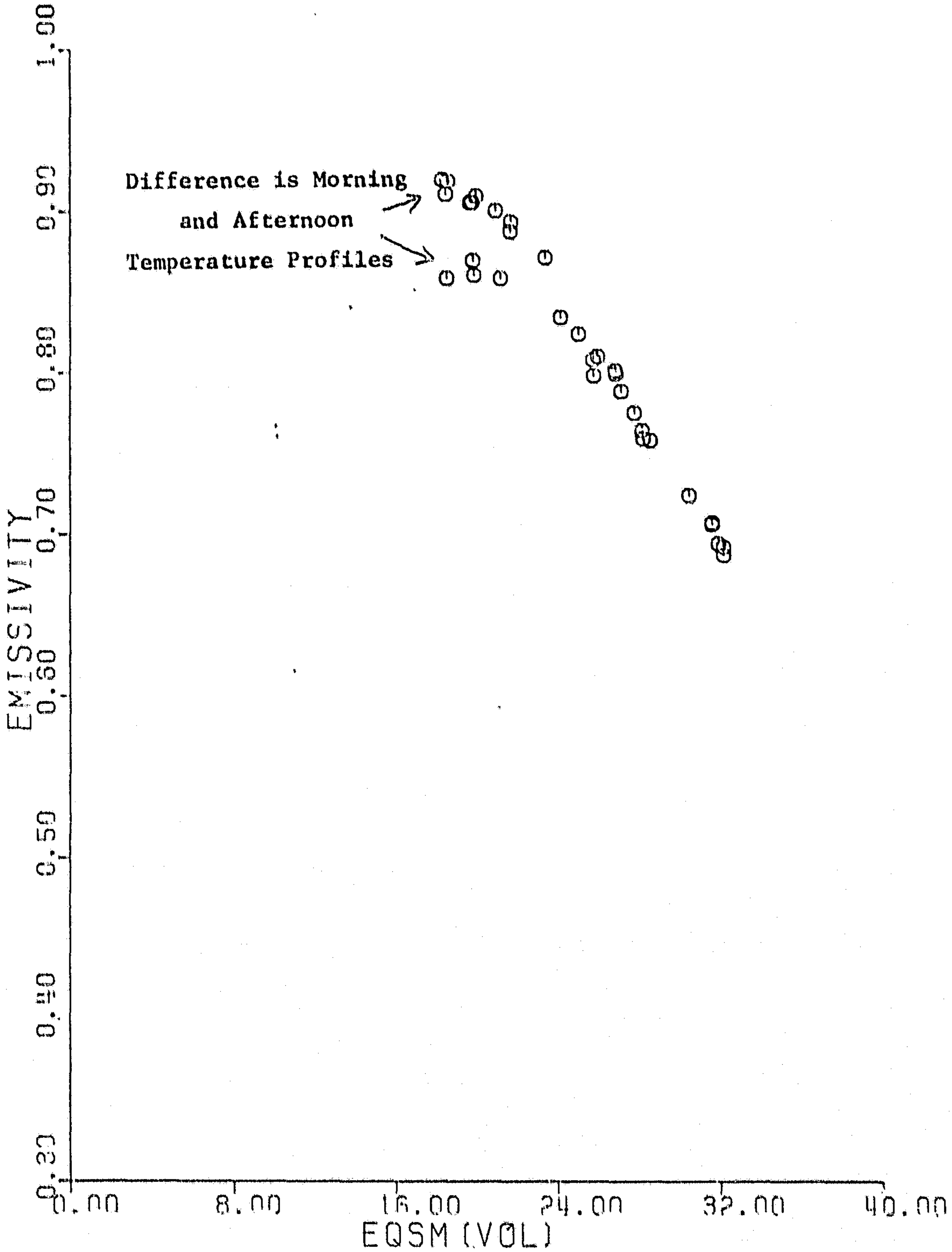

Plot of calculated surface emissivity vs. equivalent soil moisture for clay soil (Phoenix,1971,small area data)

ESTIMATING AMOUNT OF WATER IN ROOT ZONE USING TIME FREQUENCY RADIOMETER MEASUREMENTS

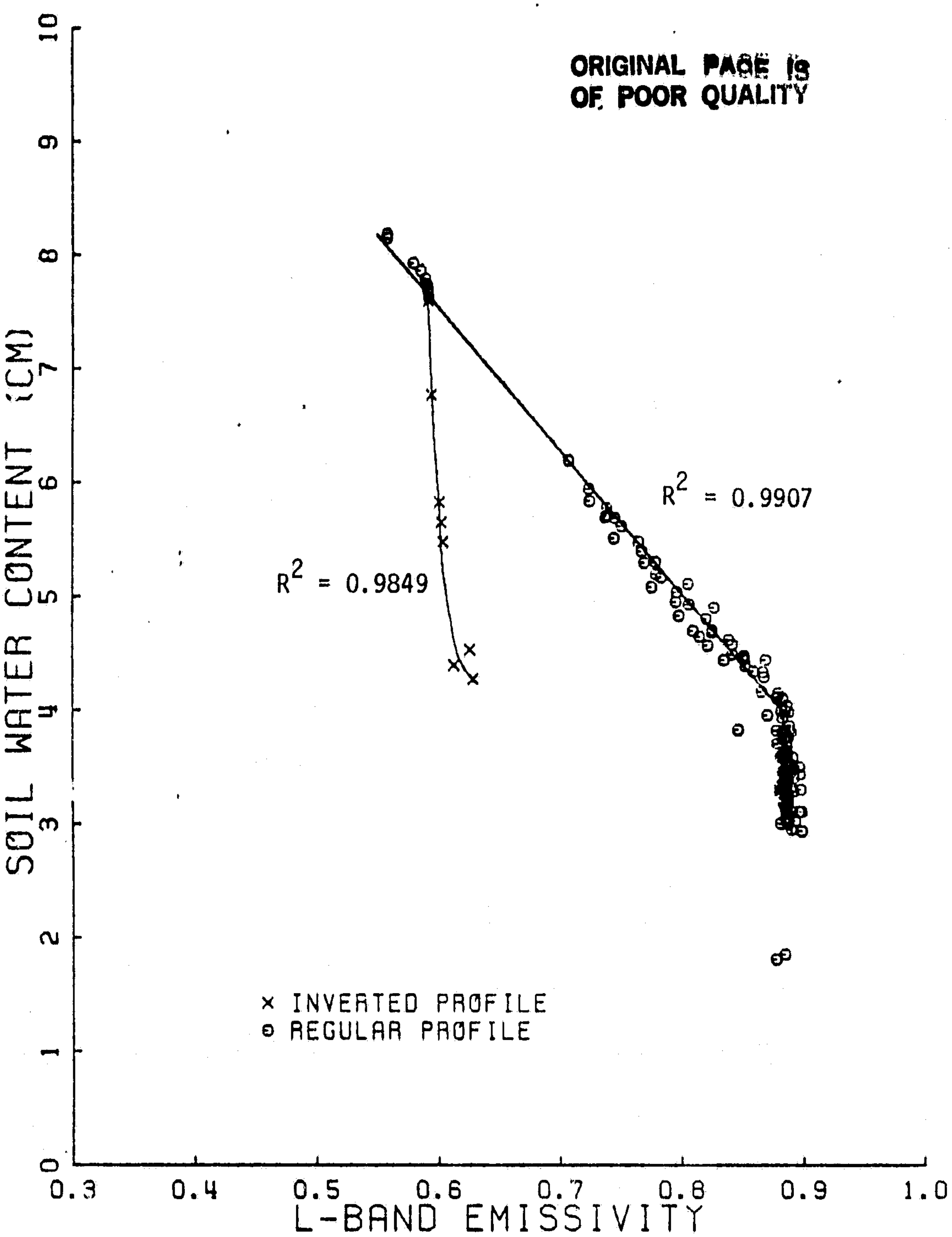

FIG. 34. Relationship between soil water content in the top 21 cm of the hypothetical loam-like soil profile and L-band emissivity as calculated by the radiative transfer model for all simulated rainfall events.

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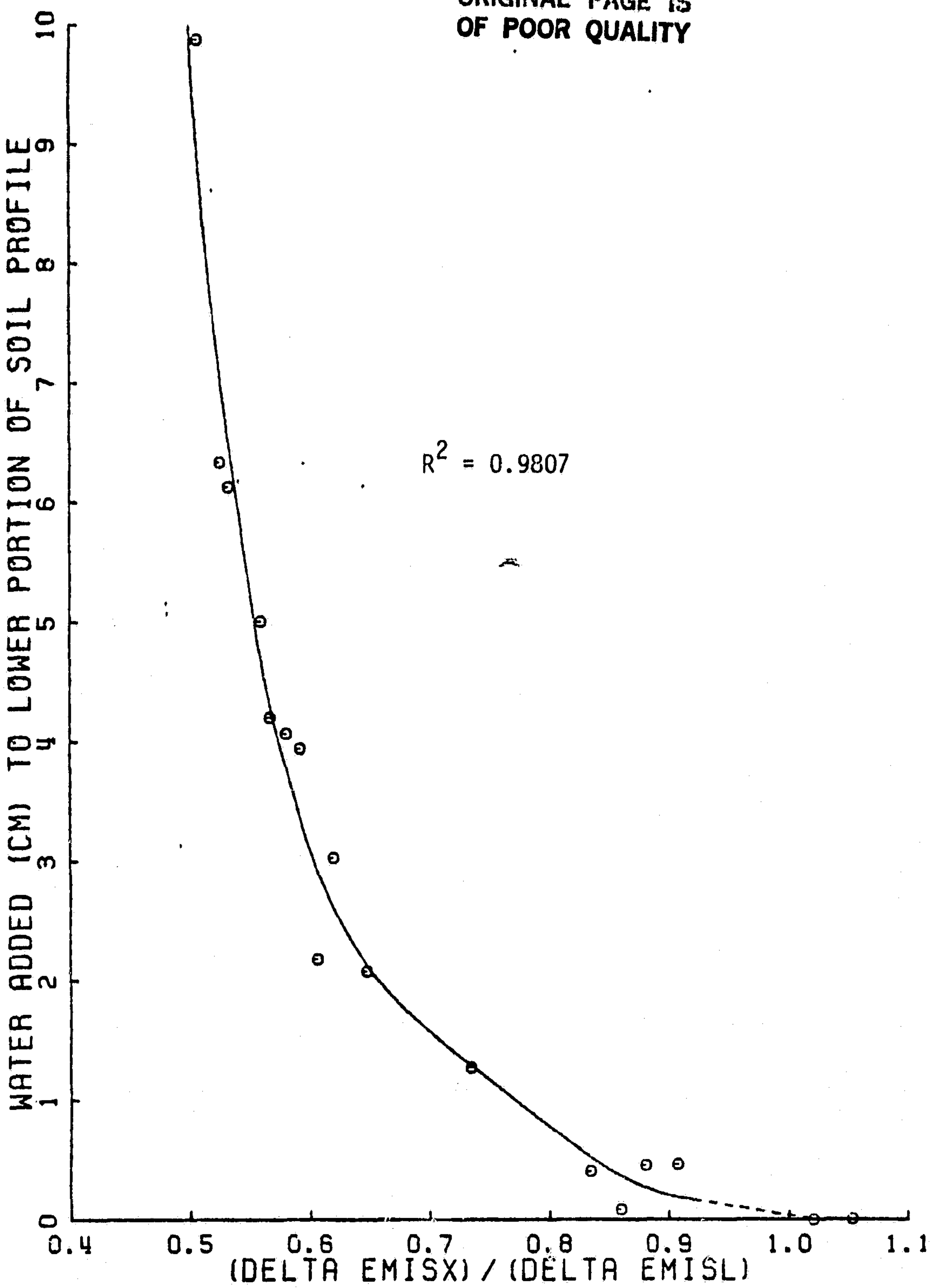

FIG. 46. Relationship between amount of water added to the hypothetical loam-like soil profile (21 to 150 cm depth) and the ratio of X-band and L-band change in emissivities one day after the rain.

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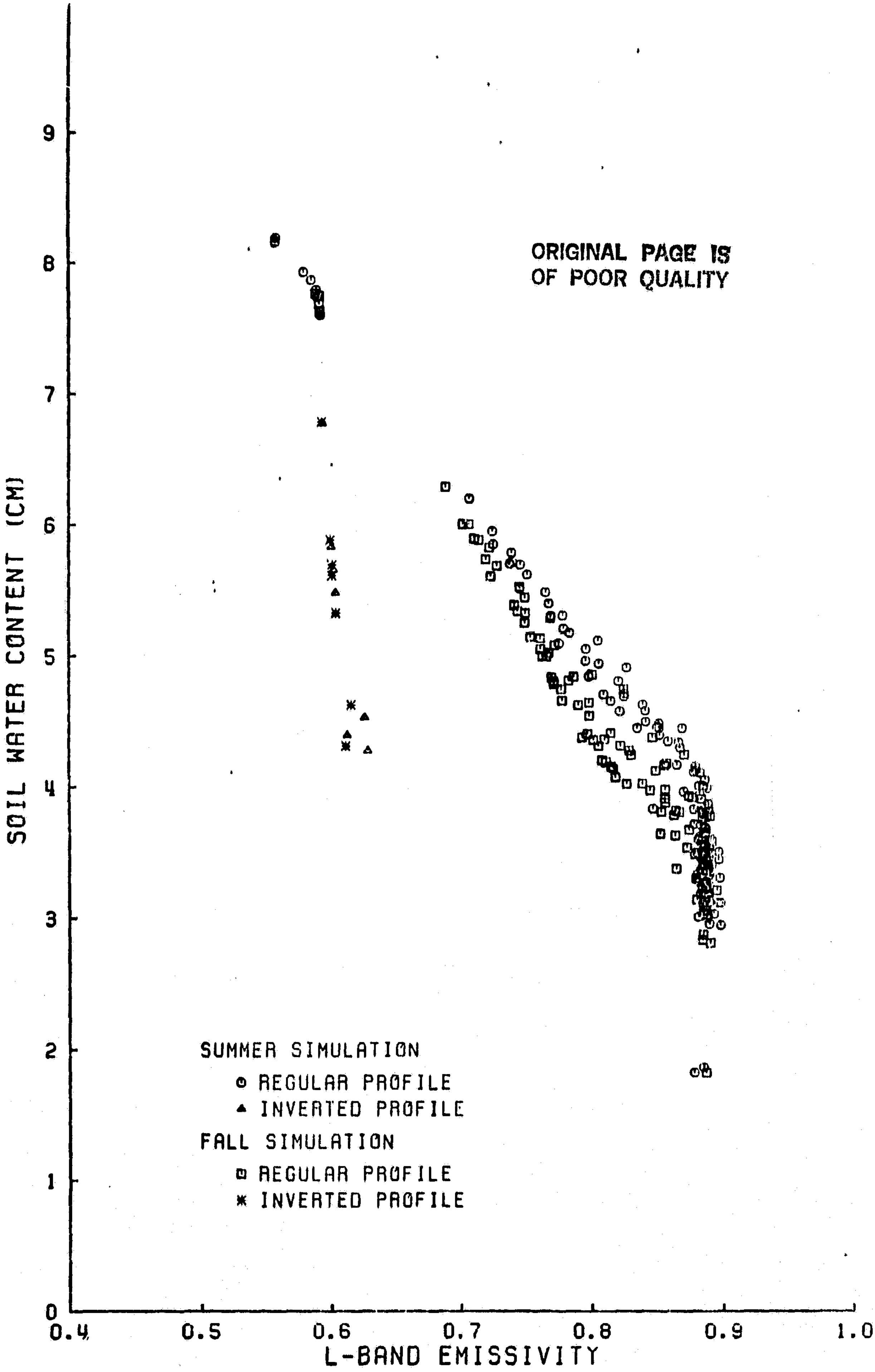

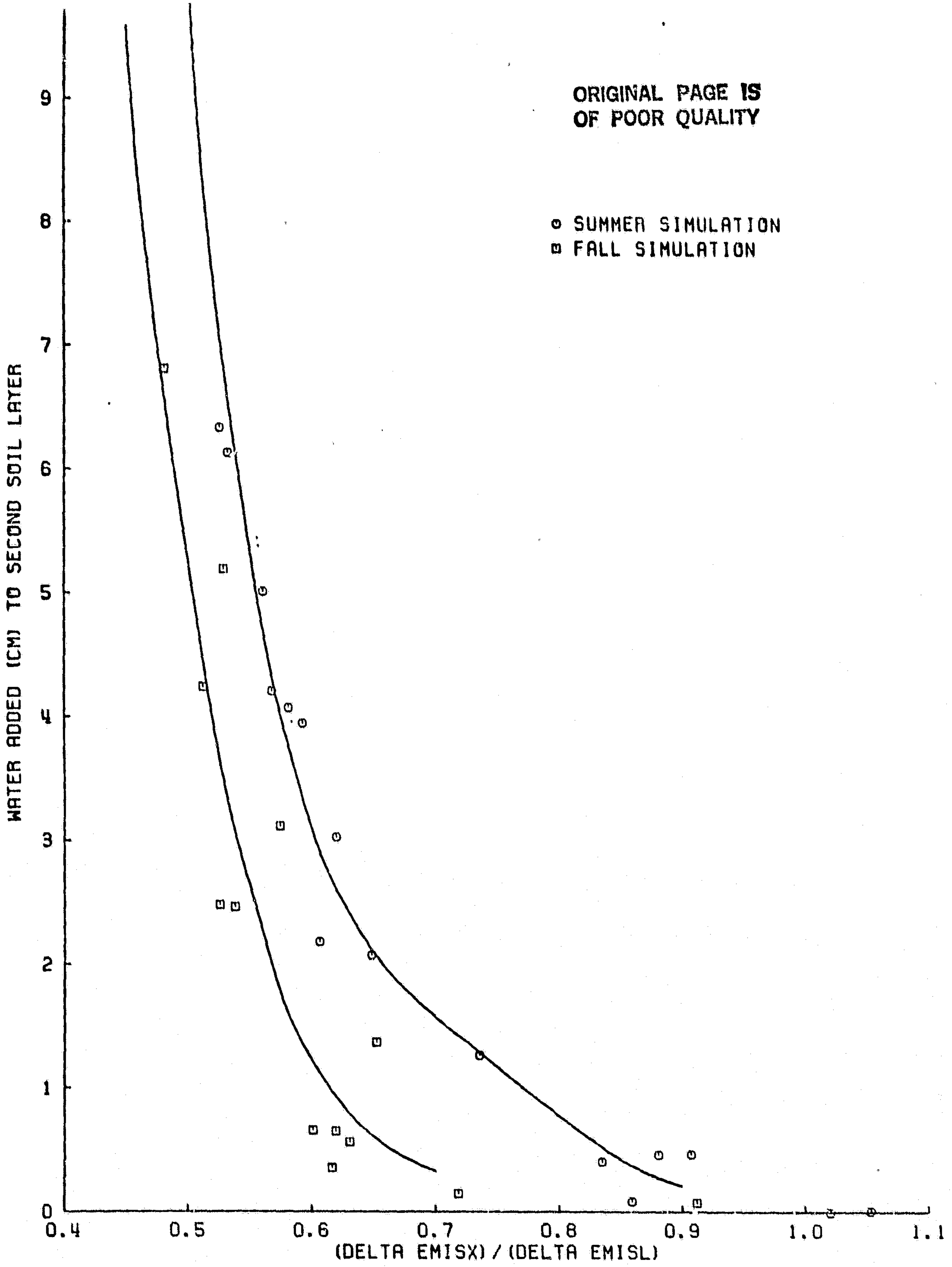

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SUMMER SIMULATION
FALL SIMULATION
WATER ADDED (CM) TO SECOND SOIL LAYER
(DELTA EMISX) / (DELTA EMISL)
0
1
2
3
4
5
6
7
8
9
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1

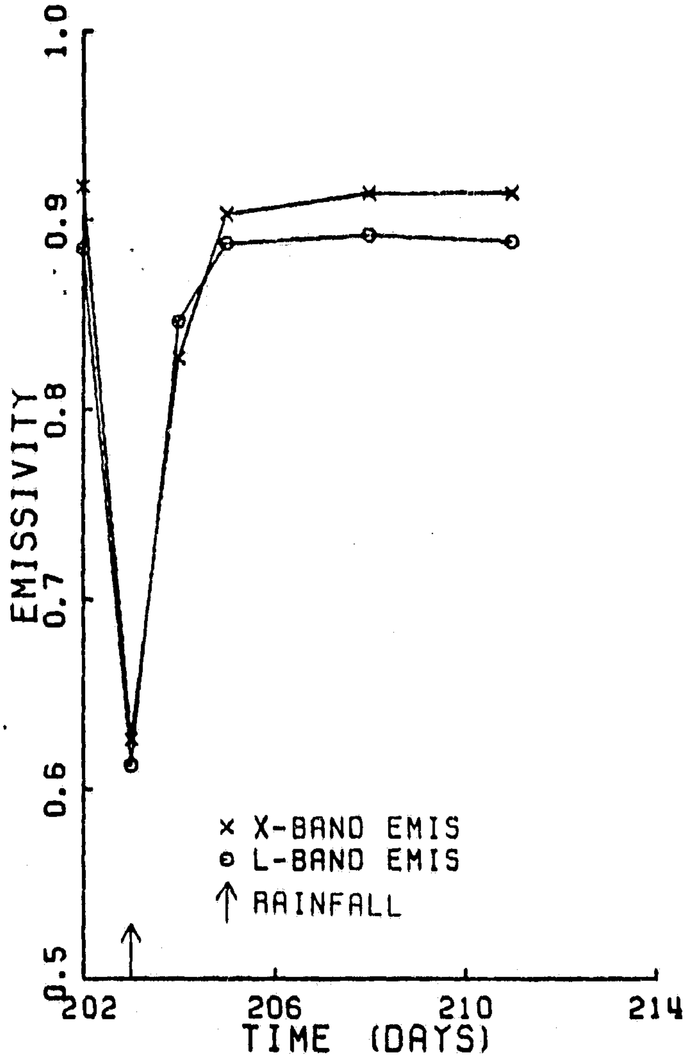

FIG. 36. X-band and L-band emissivities as calculated by the radiative transfer model versus time from a 2.54 cm rain on the hypothetical loam-like soil that was initially dry.

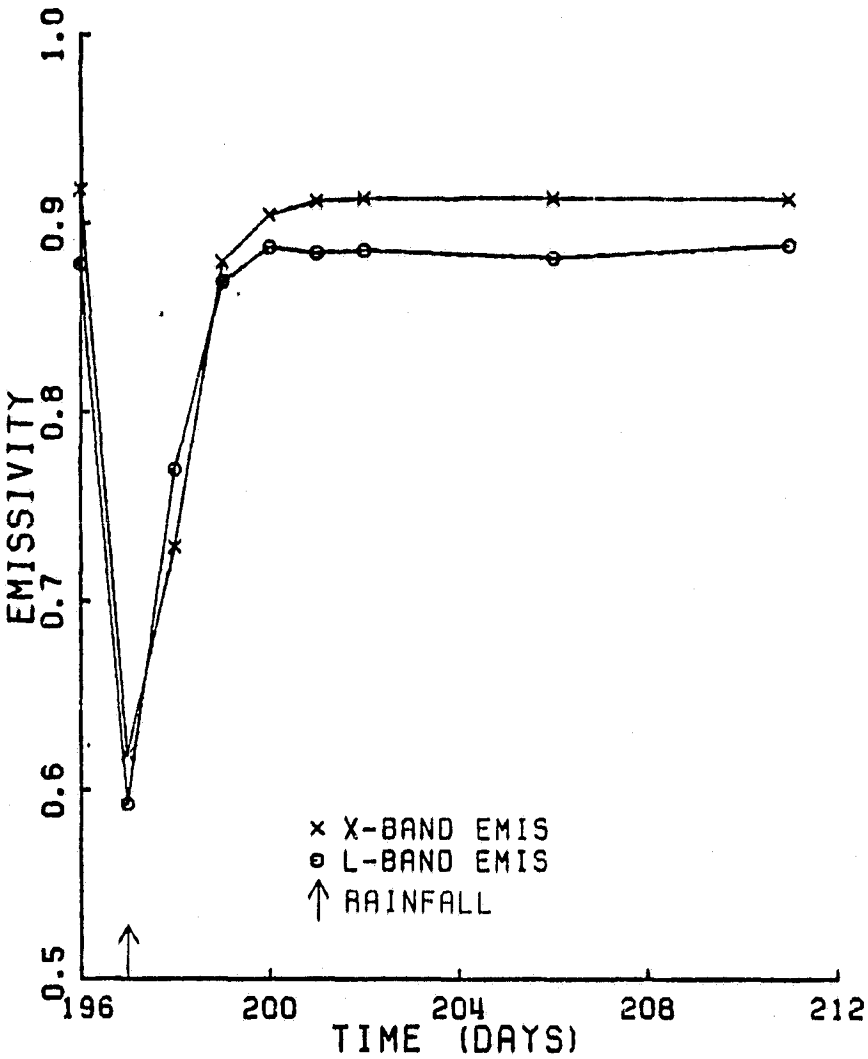

FIG. 41. X-band and L-band emissivities as calculated by the radiative transfer model versus time from a 7.62 cm rain on the hypothetical loam-like soil that was initially dry.

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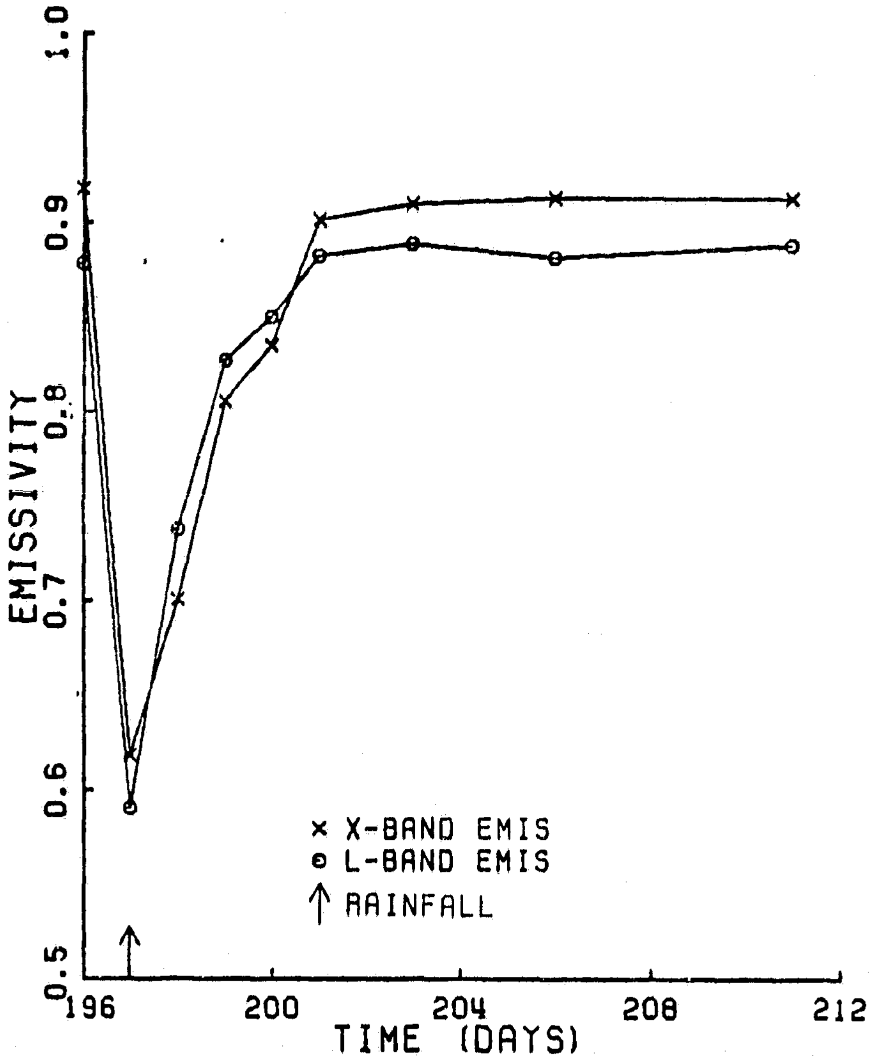


FIG. 43. X-band and L-band emissivities as calculated by the radiative transfer model versus time from a 10.16 cm rain on the hypothetical loam-like soil that was initially dry.

APPENDIX D
PRESENTATION BY JACK PARIS NASA/JSC

AgRISTARS

SOIL MOISTURE PROJECT

- USDA/SCS (PROJECT MANAGER)
- NASA/GSFC (TECHNICAL MANAGER)

<u>OBJECTIVE</u>

DEVELOP, TEST, AND EVALUATE AN INTEGRATED REMOTE SENSOR AND <u>IN SITU</u> DATA GATHERING CAPABILITY TO OBTAIN SOIL MOISTURE DATA OVER LARGE AREAS FOR AGRICULTURE, HYDROLOGY, AND CLIMATOLOGY

AgRISTARS SM
PROJECT ELEMENTS

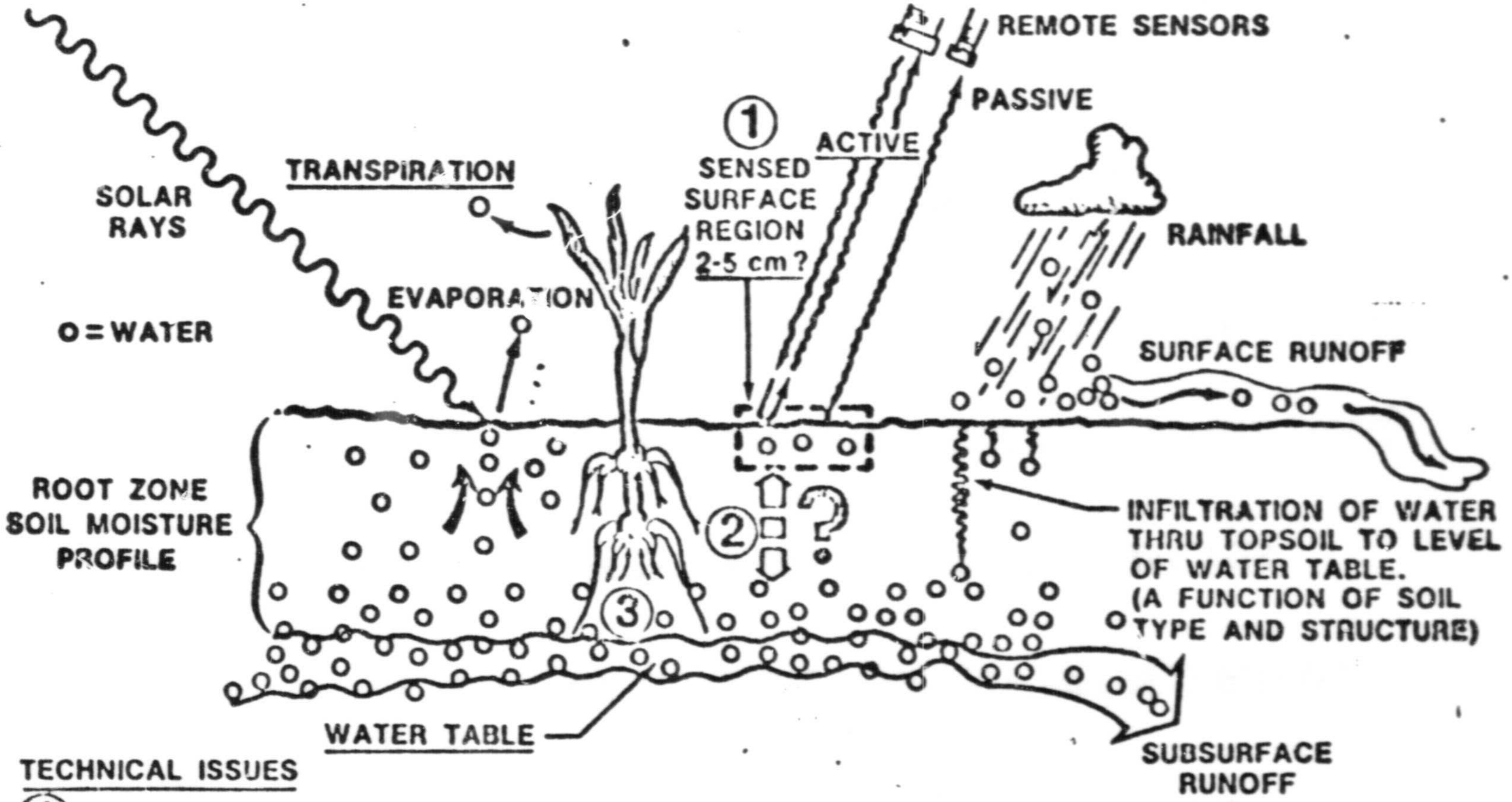
- E1 • *IN SITU* SENSOR EVALUATION
- E2 • REMOTE SENSOR FIELD MEASUREMENT
- E3 • REMOTE SENSOR AIRCRAFT MEASUREMENTS
- E4 • MODELING AND ANALYSIS

NASA/JSC TASKS
IN AgRISTARS SM

- E 2 TASK 1: REMOTE SENSOR FIELD MEASUREMENTS
- E 3 TASK 1: REMOTE SENSOR AIRCRAFT MEASUREMENTS
- E 4 TASK 1: INFORMATION EXTRACTION ANALYSIS
- E 4 TASK 4: TESTING ROOT-ZONE SOIL MOISTURE MODELS
- INTERFACING ROLES (SR, YIELD, LIT REV, SPATIAL VAR, AND SUMMARY)

NASA-S-77-11265A

AGRICULTURAL SOIL MOISTURE AND REMOTE SENSING



TECHNICAL ISSUES

(1) EXTRACTION OF SOIL MOISTURE AND DEPTH INFORMATION FROM REMOTELY SENSED SURFACE REGION

(2) MODEL ROOT ZONE SOIL MOISTURE PROFILE

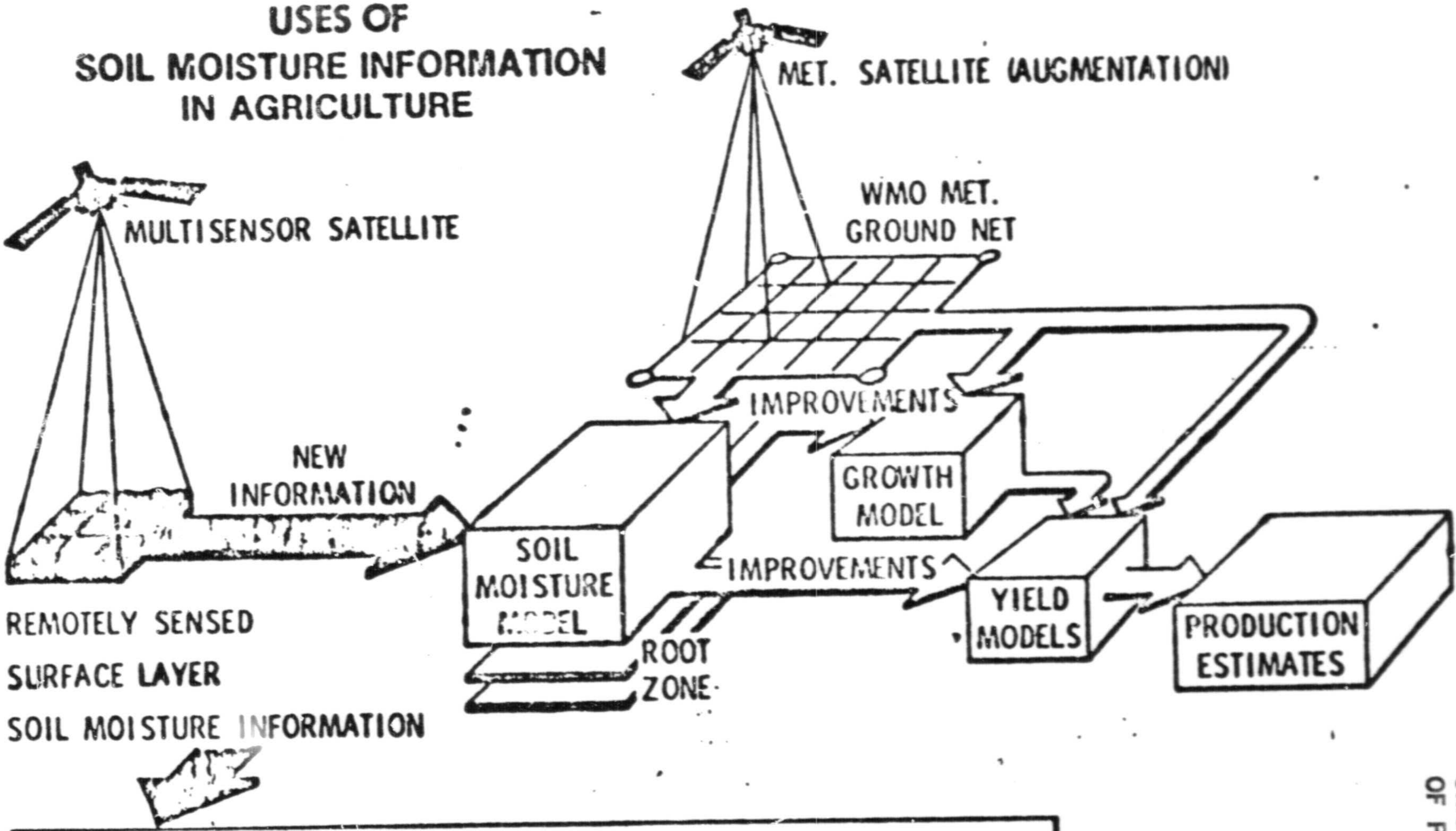
(3) DEMONSTRATE THAT REMOTELY DETERMINED ROOT ZONE SOIL MOISTURE IS AN IMPROVED REPLACEMENT OF CONVENTIONAL MOISTURE DATA IN CROP YIELD MODELS

FY77 WORK EMPHASIZED CORRELATION INVESTIGATIONS AIMED AT TECHNICAL ISSUE 1. EMPHASIS IS TO INCREASE ON ISSUE 2 & 3 SIGNIFICANTLY IN FY78

4

21

USES OF SOIL MOISTURE INFORMATION IN AGRICULTURE



OTHER USES AND BENEFITS

- SEEDBED PREPARATION
- GERMINATION PROBABILITY
- EPISODIC EVENT EFFECTS
  - WINTERKILL PROBABILITY
  - PATHOGEN LIFE CYCLE AND THREAT POTENTIAL
- CULTURAL PRACTICES
  - IRRIGATION SCHEDULING
  - TILLAGE AND DRAINAGE
- SALINE SEEP
- SOIL EROSION

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SIGNIFICANT ACCOMPLISHMENTS OF THE AgRISTARS SOIL MOISTURE PROJECT

IN FISCAL YEAR 1980

REMOTE SENSOR FIELD MEASUREMENTS (JORNADA, NEW MEX. AND PRAIRIE VIEW A&M)

1. DETERMINED THAT ROW DIRECTION WITH RESPECT TO RADAR LOOK DIRECTION SIGNIFICANTLY AFFECTS BACKSCATTERING FROM AGRICULTURAL FIELDS PLOWED IN ROWS FOR ALL FREQUENCIES STUDIED (L-, C-, and Ku-BANDS) FOR LIKE POLARIZATION (VV or HH).

2. ROW DIRECTION EFFECT IS INSIGNIFICANT FOR CROSS POLARIZED RADAR DATA (HV or VH) FOR ALL FREQUENCIES STUDIED.

3. FOUR SETS OF RADAR DATA WERE ACQUIRED TO SUPPORT 1 AND 2 ABOVE (2 IN FALL 79 AND 2 IN LATE SUMMER 80).

REMOTE SENSOR AIRCRAFT MEASUREMENTS (COLBY, KANSAS, ASME 1978)

1. PREPROCESSING OF AIRCRAFT RADIOMETER (IR AND MICROWAVE) AND RADAR SCATTEROMETER DATA COMPLETED FOR 3 OF 7 FLIGHT DAYS AND FOR PART OF FLIGHT DAY 4.

2. ANALYSES OF DATA TAKEN ON FLIGHT DAYS 1 AND 2 COMPLETED BY UNIVERSITY OF KANSAS.

   A. FOUND EXCELLENT COMPARISON BETWEEN AIRCRAFT RADAR SCATTEROMETER DATA AND GROUND-BASED RADAR SCATTEROMETER DATA WHICH INCREASES CONFIDENCE IN CONCLUSIONS REACHED IN PAST BASED UPON GROUND-BASED RADAR DATA.

   B. CONFIRMED EXPECTED EFFECT OF SOIL MOISTURE CHANGES FROM DAY TO DAY ON RADAR SCATTEROMETER AND MICROWAVE RADIOMETER MEASUREMENTS FROM DAY TO DAY OVER 40 FIELDS.

   C. SHOWED SIGNIFICANT EFFECT OF ROW DIRECTION ON AIRCRAFT SCATTEROMETER MEASUREMENTS AT ALL FREQUENCIES USED FOR LIKE POLARIZATION.

   D. SHOWED INSIGNIFICANT EFFECT OF ROW DIRECTION ON AIRCRAFT SCATTEROMETER MEASUREMENTS AT ALL FREQUENCIES USED FOR CROSS POLARIZATION.

MODELING AND ANALYSIS (IN-HOUSE)

1. EVALUATED SPATIAL VARIABILITY OF IN SITU SOIL MOISTURE MEASUREMENTS USED FOR SUPPORT TO FIELD AND AIRCRAFT MEASUREMENTS.

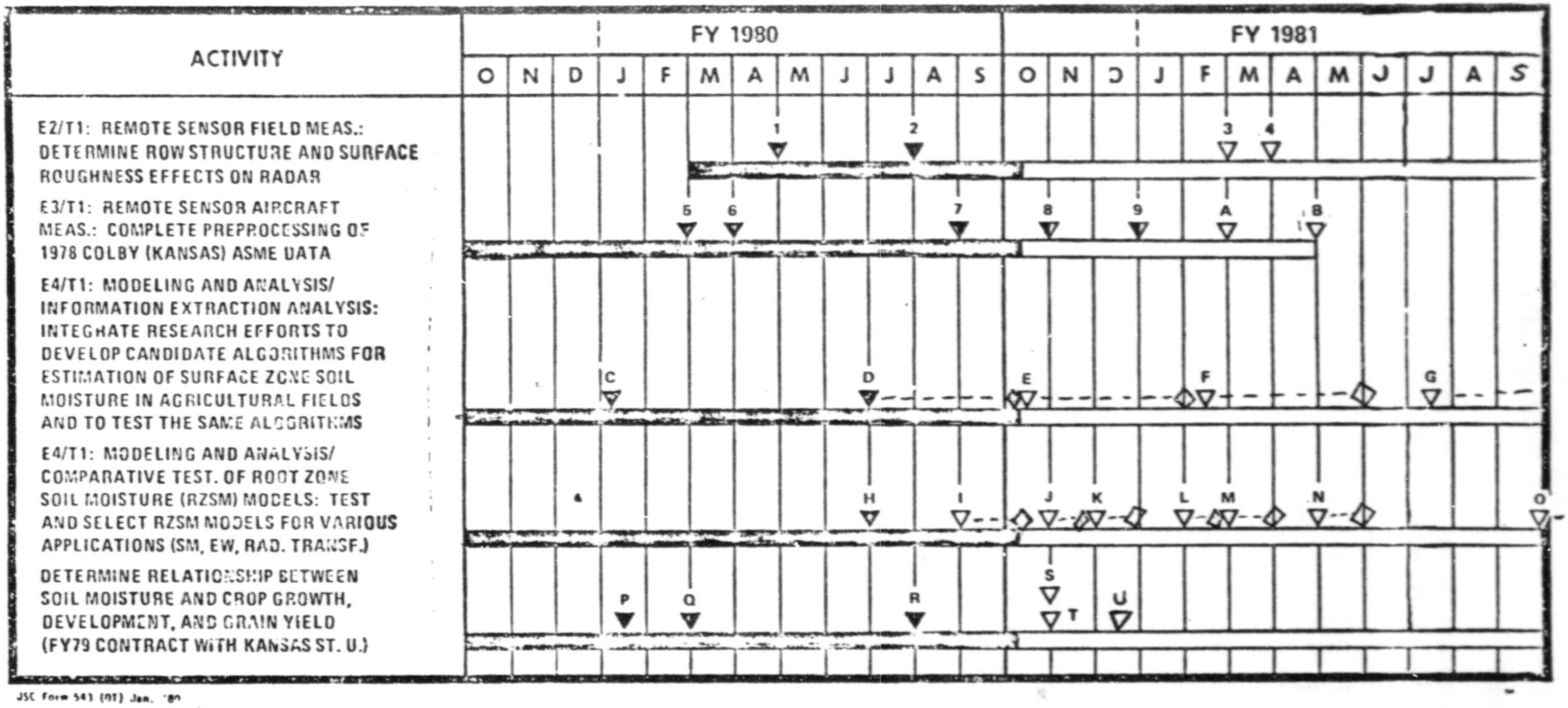
2. DEVELOPED A PHYSICAL MODEL (MATH MODEL) TO PREDICT THE WATER CHARACTERISTIC OF ANY SOIL GIVEN SOIL TEXTURE, BULK DENSITY, AND SOIL SWELLING CHARACTERISTICS. THE WATER CHARACTERISTIC IS THE RELATIONSHIP BETWEEN SOIL WATER PRESSURE (OR TENSION) AND SOIL MOISTURE CONTENT (VOLUMETRIC OR GRAVIMETRIC).

3. IMPROVED UPON A RADIATIVE TRANSFER MODEL TO PREDICT THE INFRARED AND MICROWAVE EMISSION CHARACTERISTICS OF A SOIL GIVEN THE VERTICAL DISTRIBUTION OF SOIL MOISTURE AND TEMPERATURE.

4. TRANSFERED SOIL MOISTURE PROFILE PREDICTION MODELS TO JSC COMPUTER SYSTEM AND INITIATED A DETERMINATION OF THE SENSITIVITY OF MODEL OUTPUT PREDICTIONS TO ERRORS IN MODEL INPUTS (VAN BAVEL WATBAL1).

5. HELD A WORKSHOP IN JANUARY 1980 TO EVALUATE THE PROBABLE INPACT OF MEASURED SOIL MOISTURE DATA ON CROP GROWTH, DEVELOPMENT, AND GRAIN YIELD ESTIMATION.

SOIL MOISTURE PROJECT



MILESTONE DESCRIPTIONS:

1	Experiment Plan drafted (FY80)
2	Ground Scatterometer System completion
3	Bare soil data acquisition and analysis completed
4	Experiment Plan drafted (FY81)
5	Ground Truth Data Analyses Completed
6	Preprocessing requirements sent to AIRP
7-B	Complete preprocessing and distribution for days 3-7
C	Initiate literature review for candidate algorithms
D	Add LEMSCO programmer support
E	Select candidate algorithms for bare soil
F	Complete testing of bare soil algorithm with Colby data
G	Select candidate algorithms for crops
H	Complete descriptions of models to be tested
I-M	Determine sensitivity of model outputs to errors in model inputs: Van Bavel (I), Hank (J), Saxton (K), VSMB (L), Kanemasu [illegible] model (M)
N	Locate data sets suitable for comparative testing of models
O	Recommend specific models for early warning, RZSM estimation from surface zone soil moisture measurement, and radiative transfer modeling
P	KSU Workshop
Q-S	Contract reports (Q) draft, (R) workshop, (S) final
T	NEW CONTRACT (KSU)
U	RFP FOR SM IMPACT ASSESSMENT

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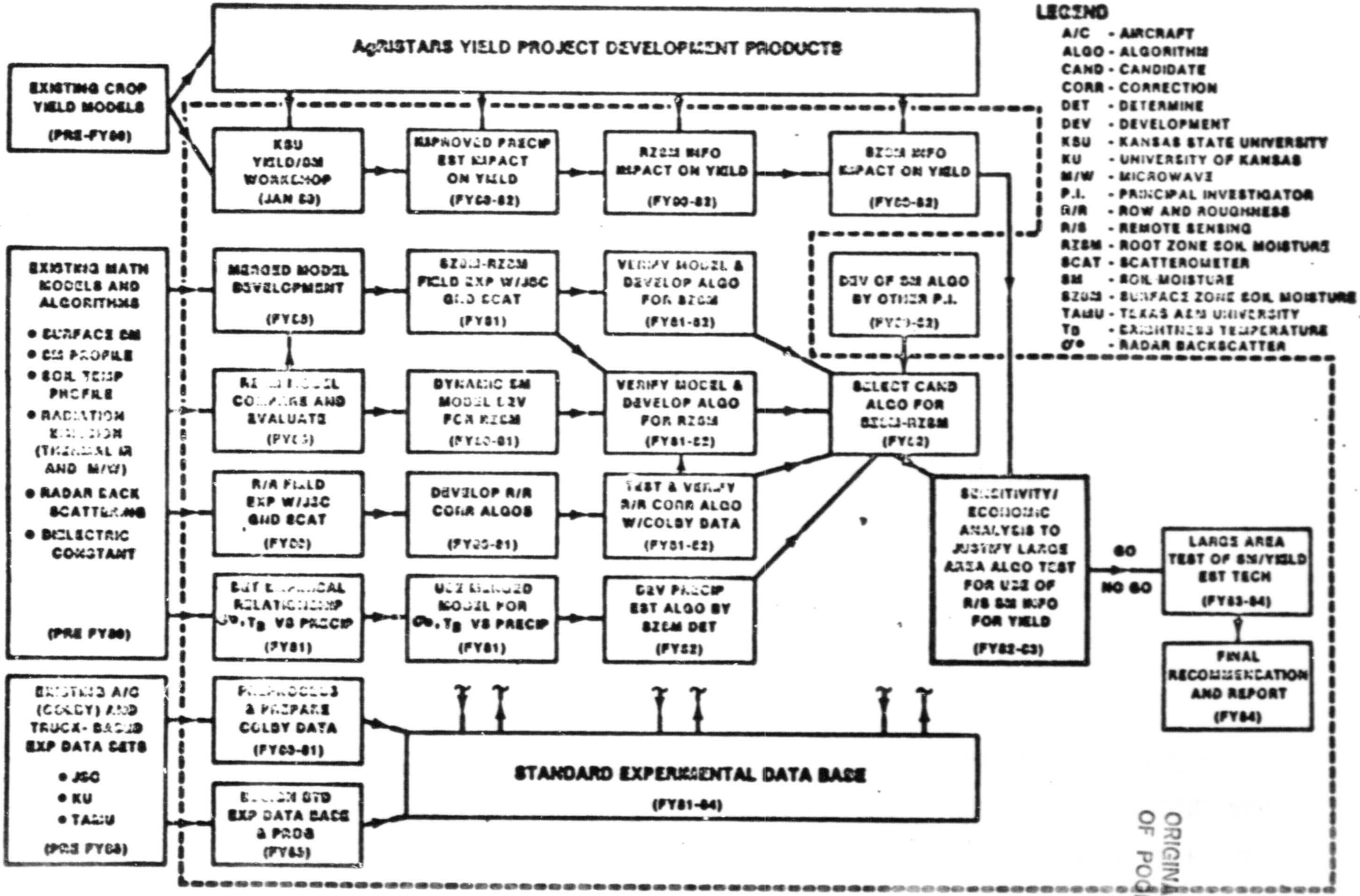
NASA/JSC - AgRISTARS SOIL MOISTURE PROJECT



ROUGHNESS/ROW DIRECTION EFFECTS EXPERIMENT (E2/T1)

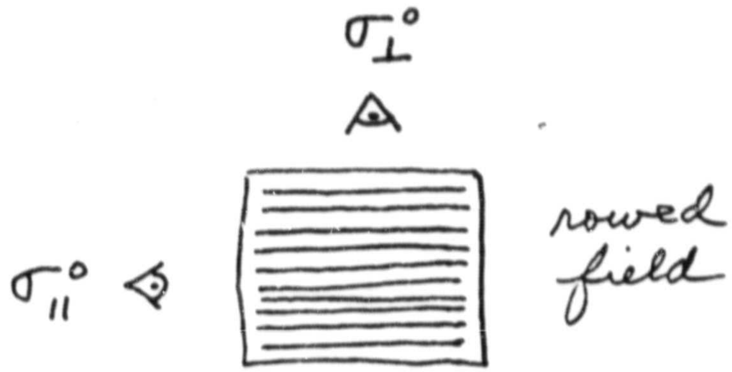
OBJECTIVE (PIP): TO DETERMINE STATISTICALLY THE DEPENDENCE OF RADAR MEASUREMENTS ON AGRICULTURAL PRACTICES, E.G., ROW HEIGHT, SPACING AND AND DIRECTION, AND ROUGHNESS EFFECTS VERSUS POLARIZATION FREQUENCY AND LOOK ANGLE

ACTIVITIES:

- SELECTION OF PVAMU TEST SITE
- COMPLETION OF JSC GROUND SCATTEROMETER SYSTEM
- PHASE I: CHARACTERIZATION OF THE DISTRIBUTION OF GROUND-TRUTH AND RADAR MEASUREMENTS TO PROVIDE BASIS FOR EXPERIMENTAL DESIGN (MAY-JUNE 80)

LOOK DIRECTION

MODULATION FUNCTION



$$M = \frac{\sigma_\perp^o}{\sigma_\parallel^o}$$

In db,

$$M(db) = \sigma_\perp^o(db) - \sigma_\parallel^o(db)$$

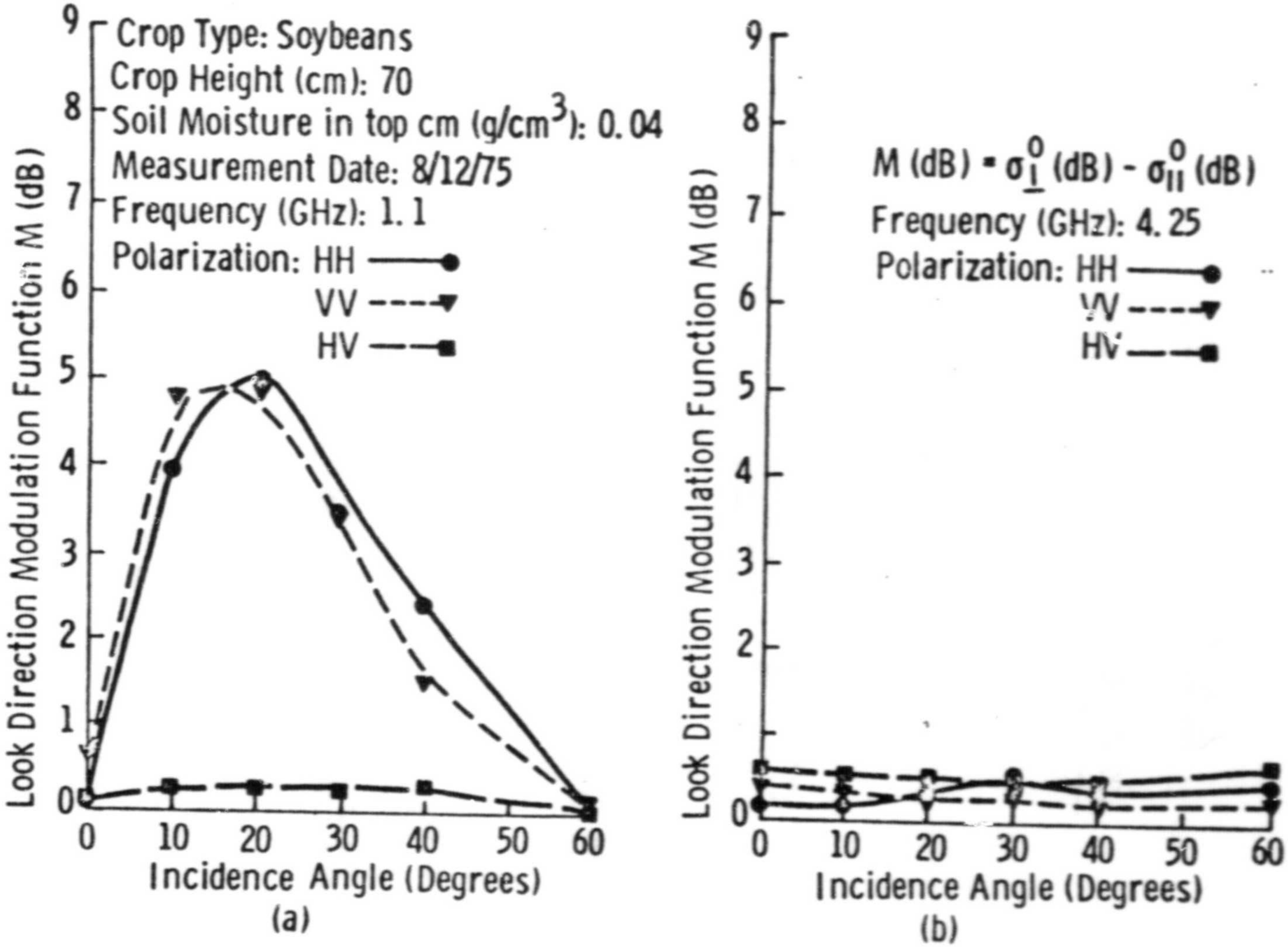


Figure 15. Comparison of the angular response of the look direction modulation function of a soybean field for HH, HV and VV polarizations at a) 1.1 GHz and b) 4.25 GHz (adapted from Batlivala and Ulaby, 1977b).

JSC GROUND SCATTEROMETER SYSTEM

- 50 FT BOOM
-

L	C	K_U
1.6 GHz	4.75 GHz	13.3 GHz
19 CM	6.3 CM	2.3 CM

- BEAMWIDTH (ALONG X CROSS)

8^0X8^0	3^0X3^0	7^0X8^0

- VIEWING ANGLES: $10^0 - 60^0$
- BANDWIDTH: 1 GHz (SWEEP)

  1-4 kHz (INSTANTANEOUS)

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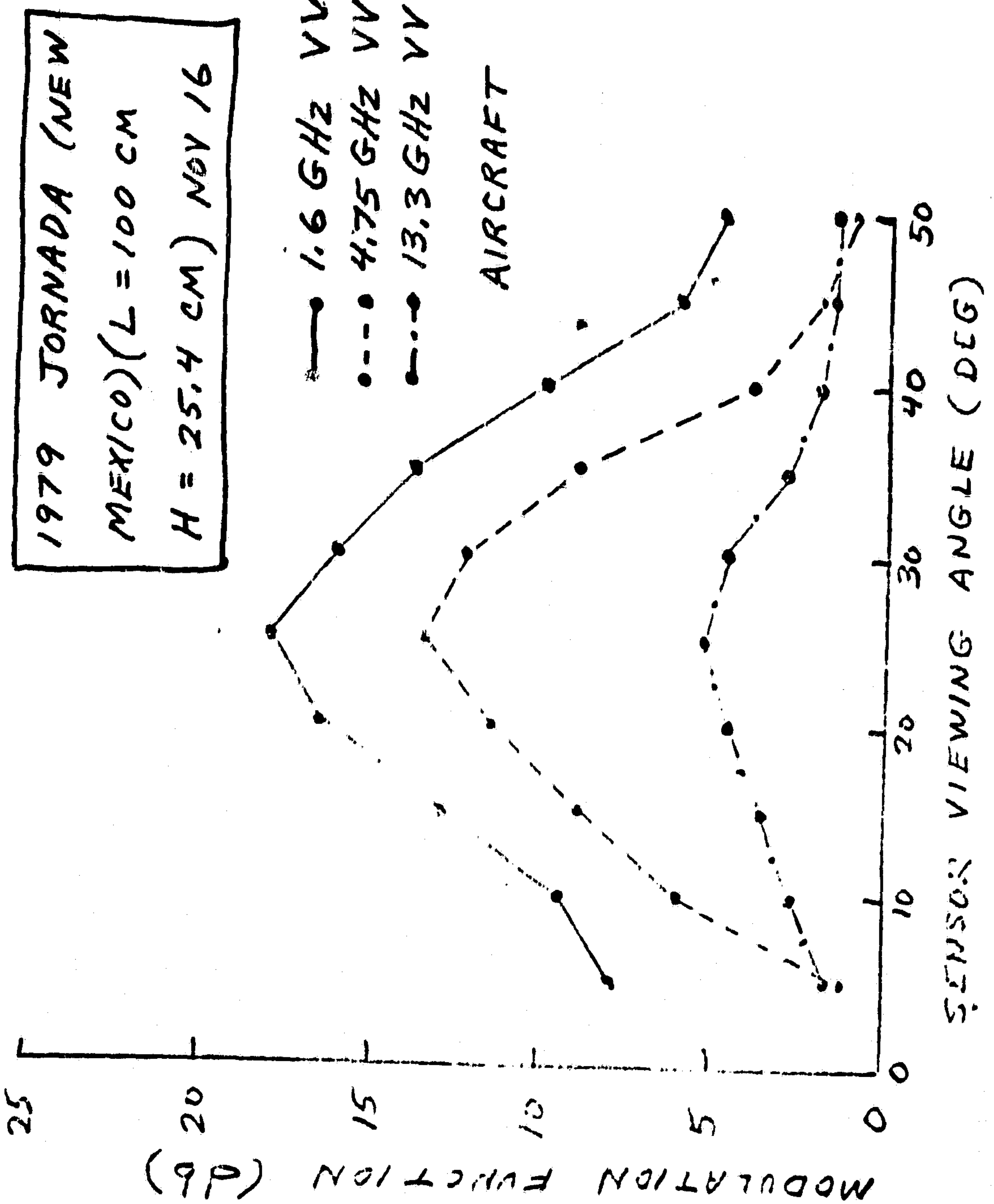

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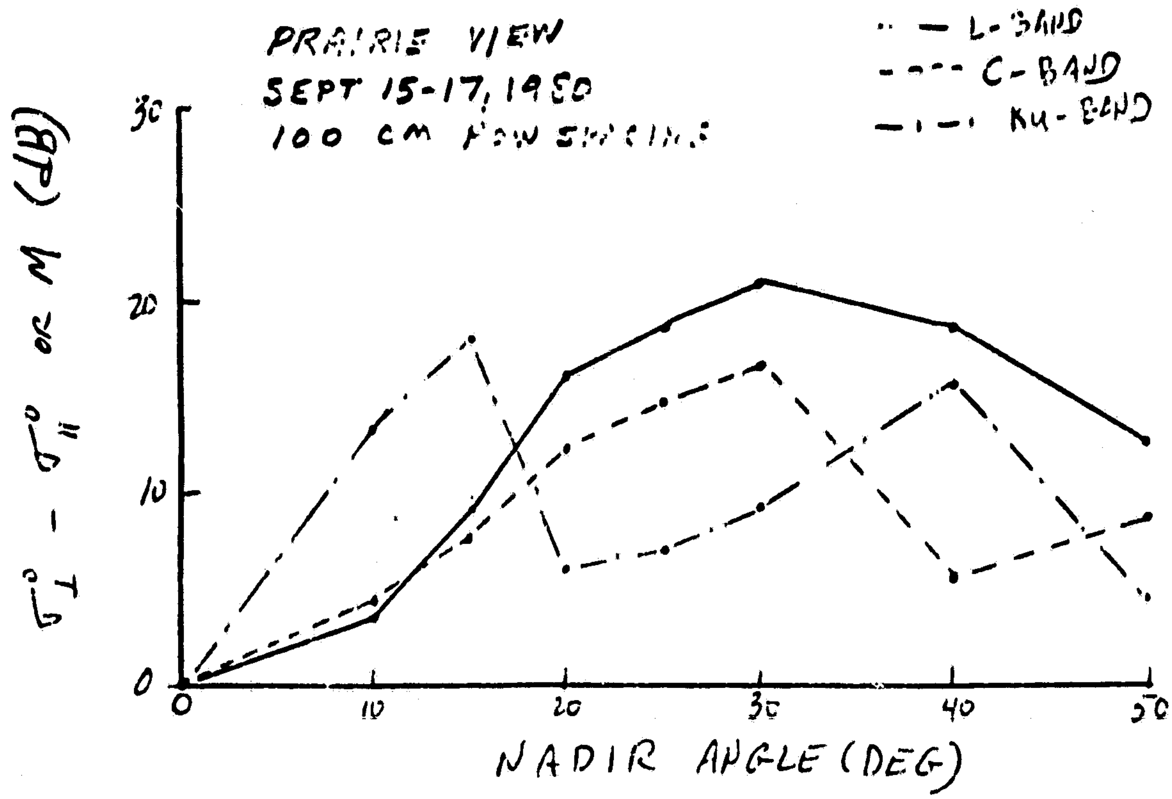
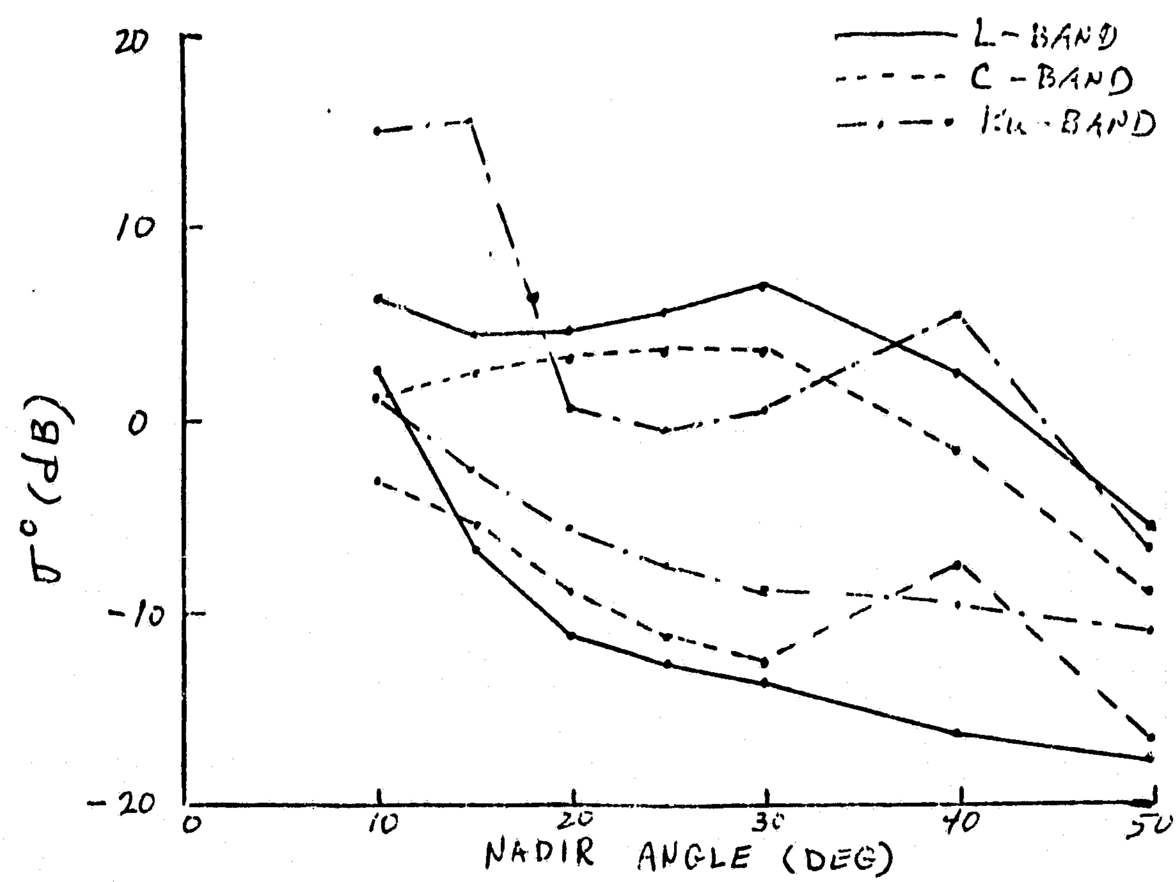




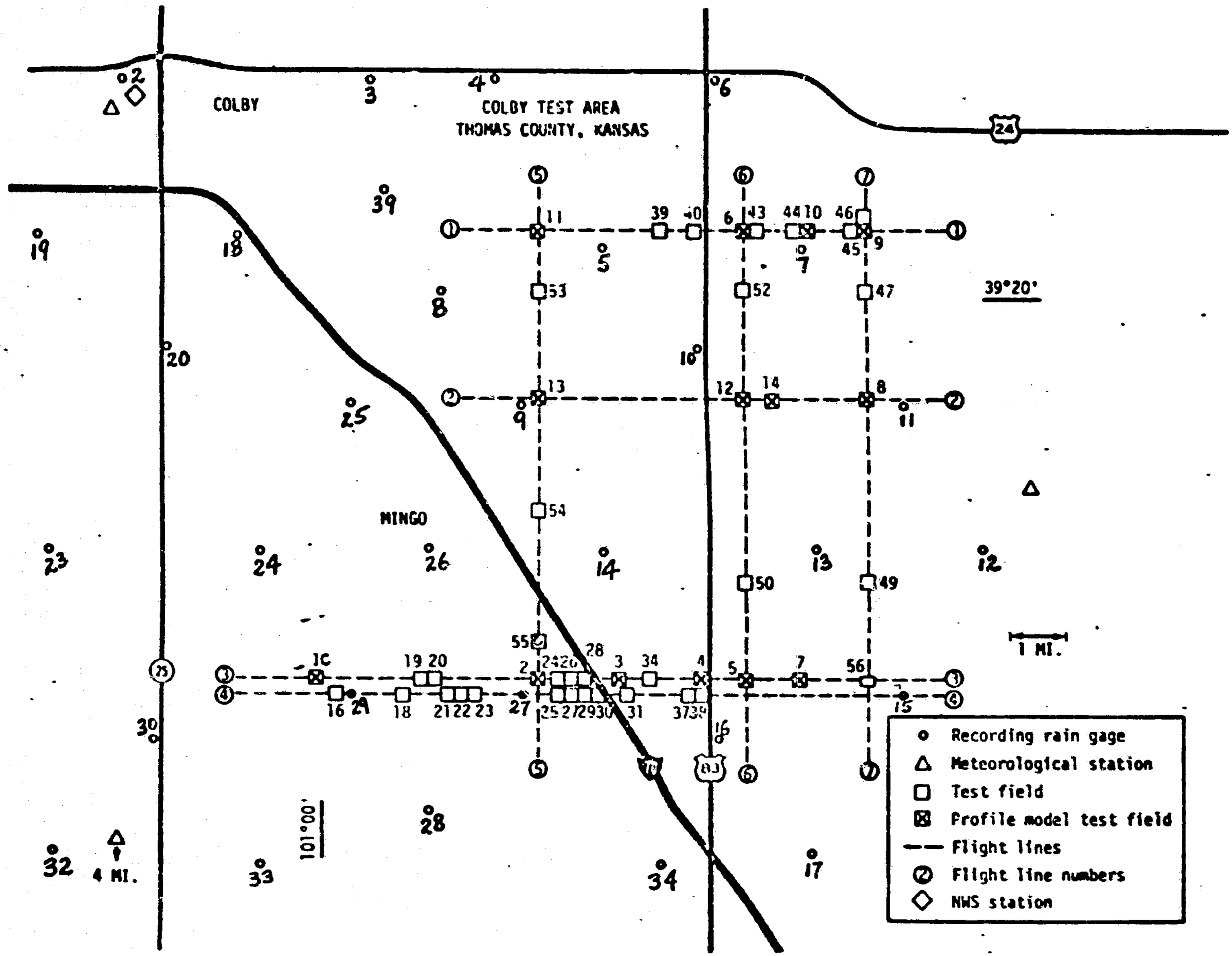
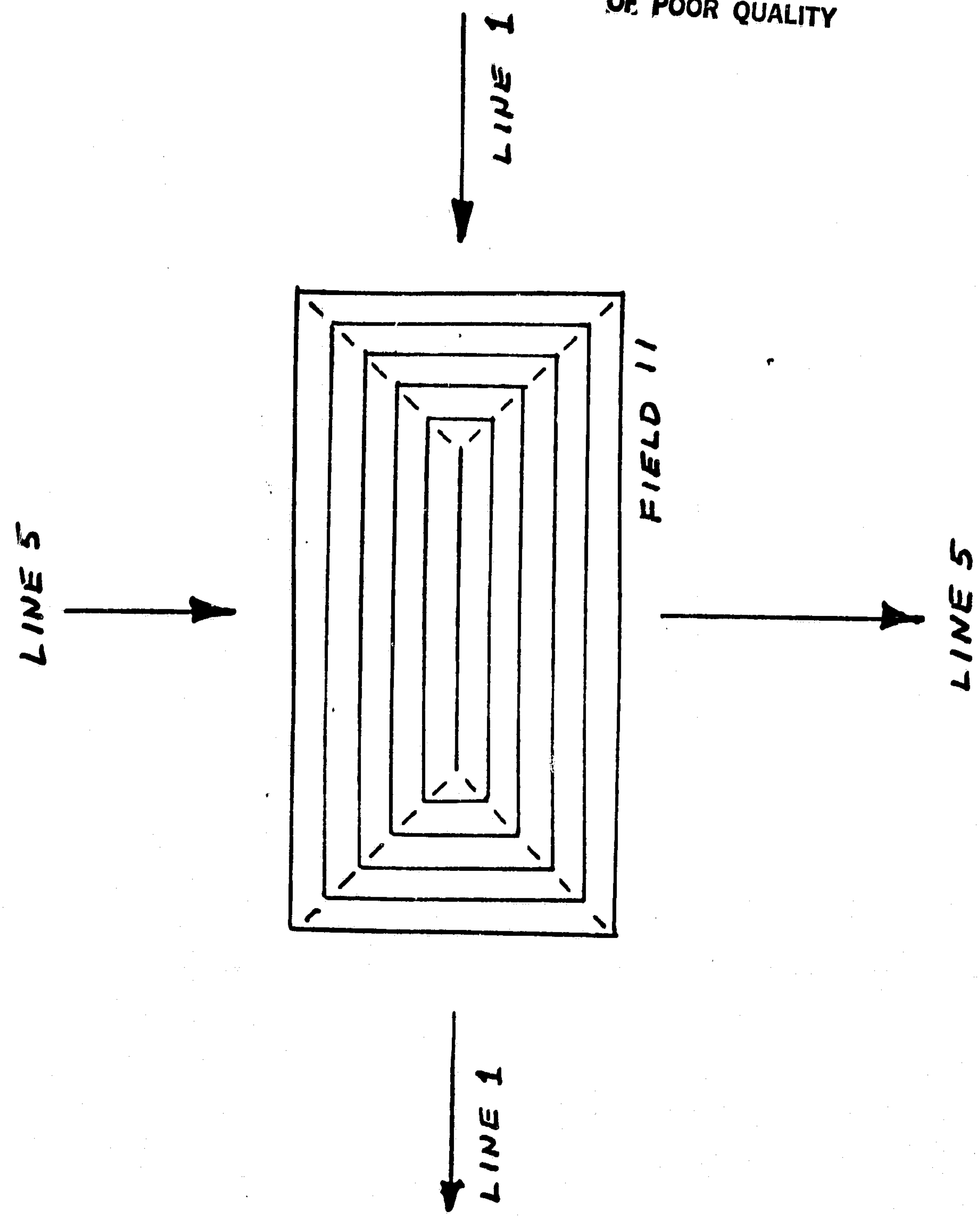
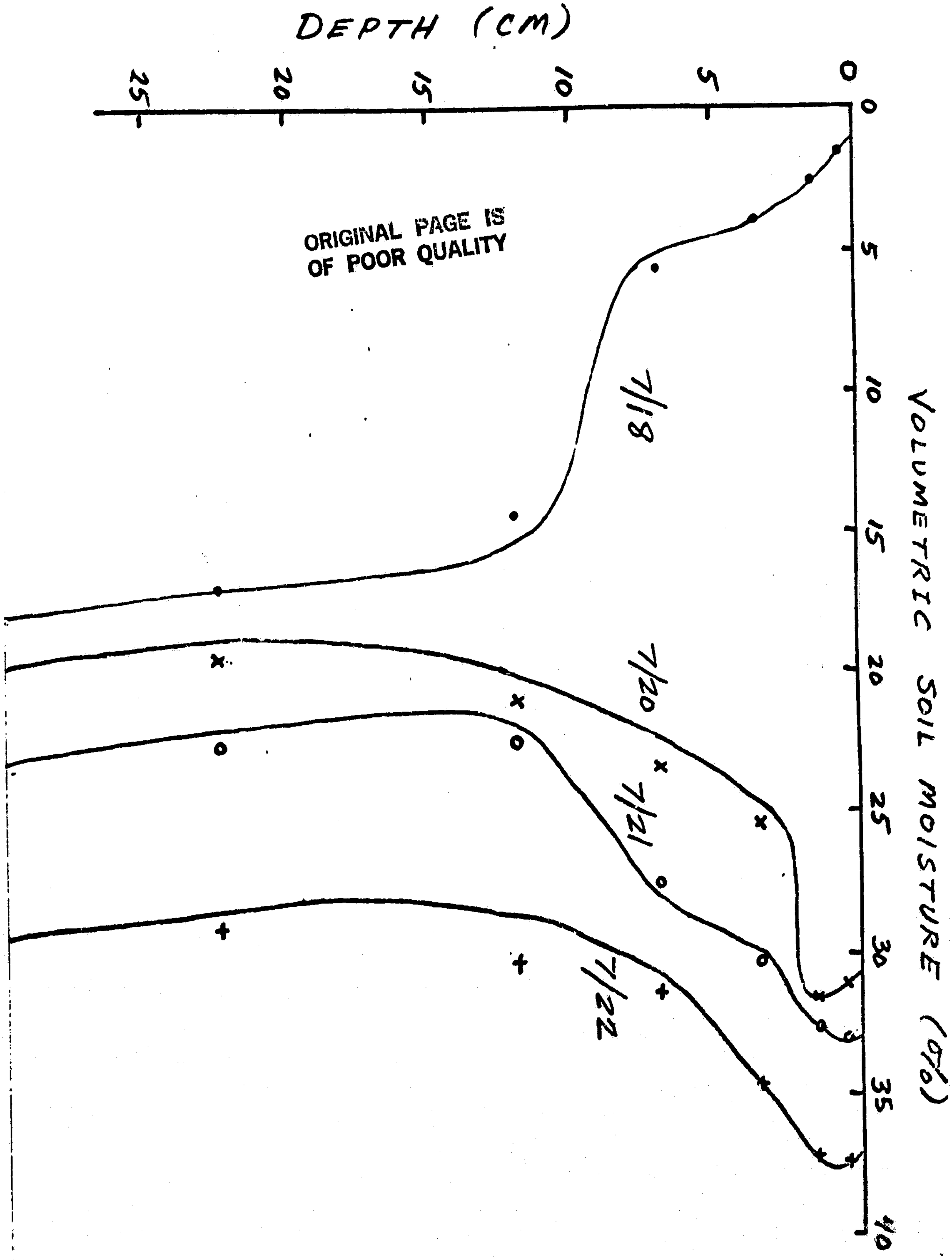


Figure 1.— Locations of the test fields used for data acquisition.


LINE 1
FIELD 11
LINE 5
LINE 5
LINE 1


DEPTH (CM)
0
5
10
15
20
25
VOLUMETRIC SOIL MOISTURE (%)
0
5
10
15
20
25
30
35
40
7/18
7/20
7/21
7/22

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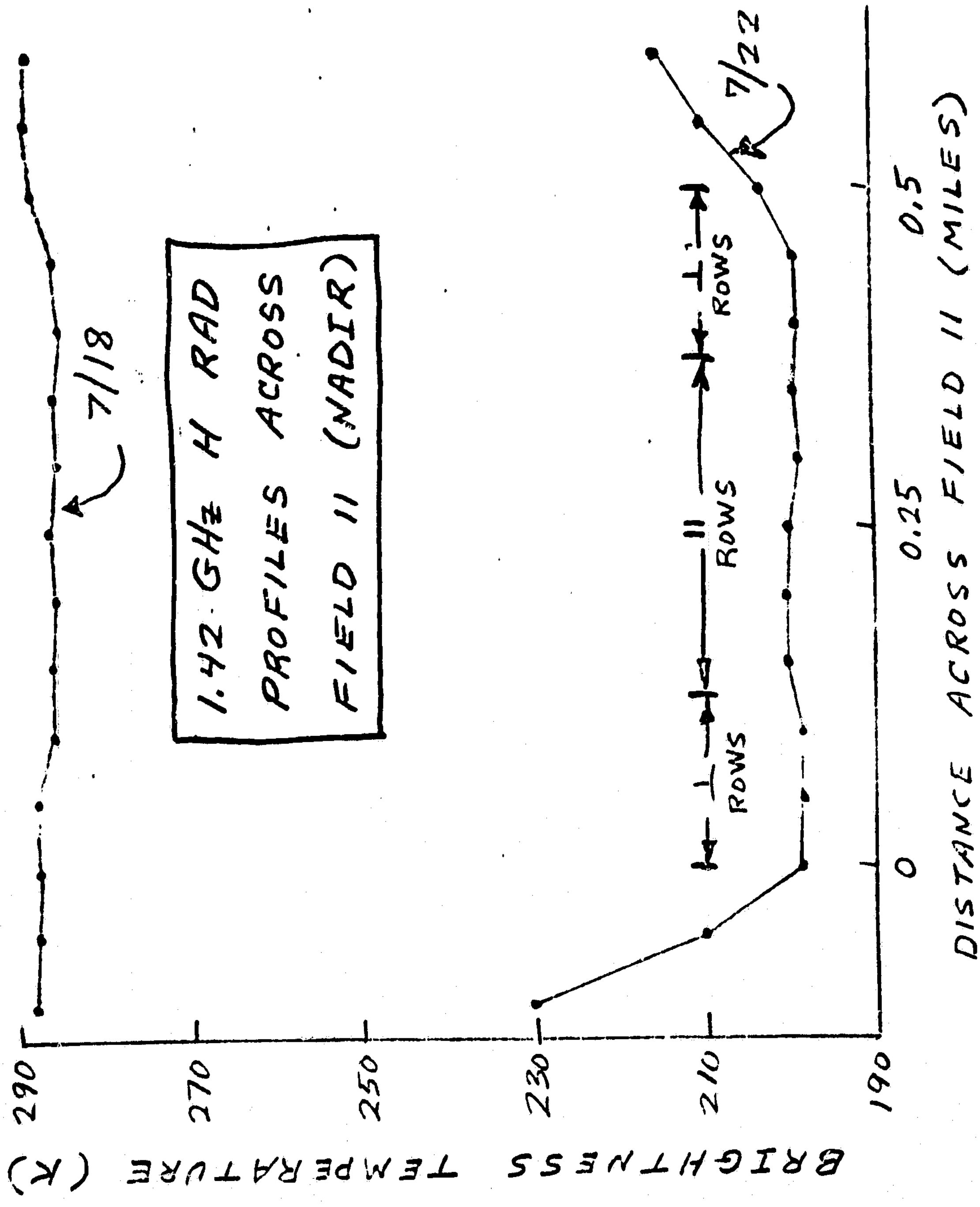

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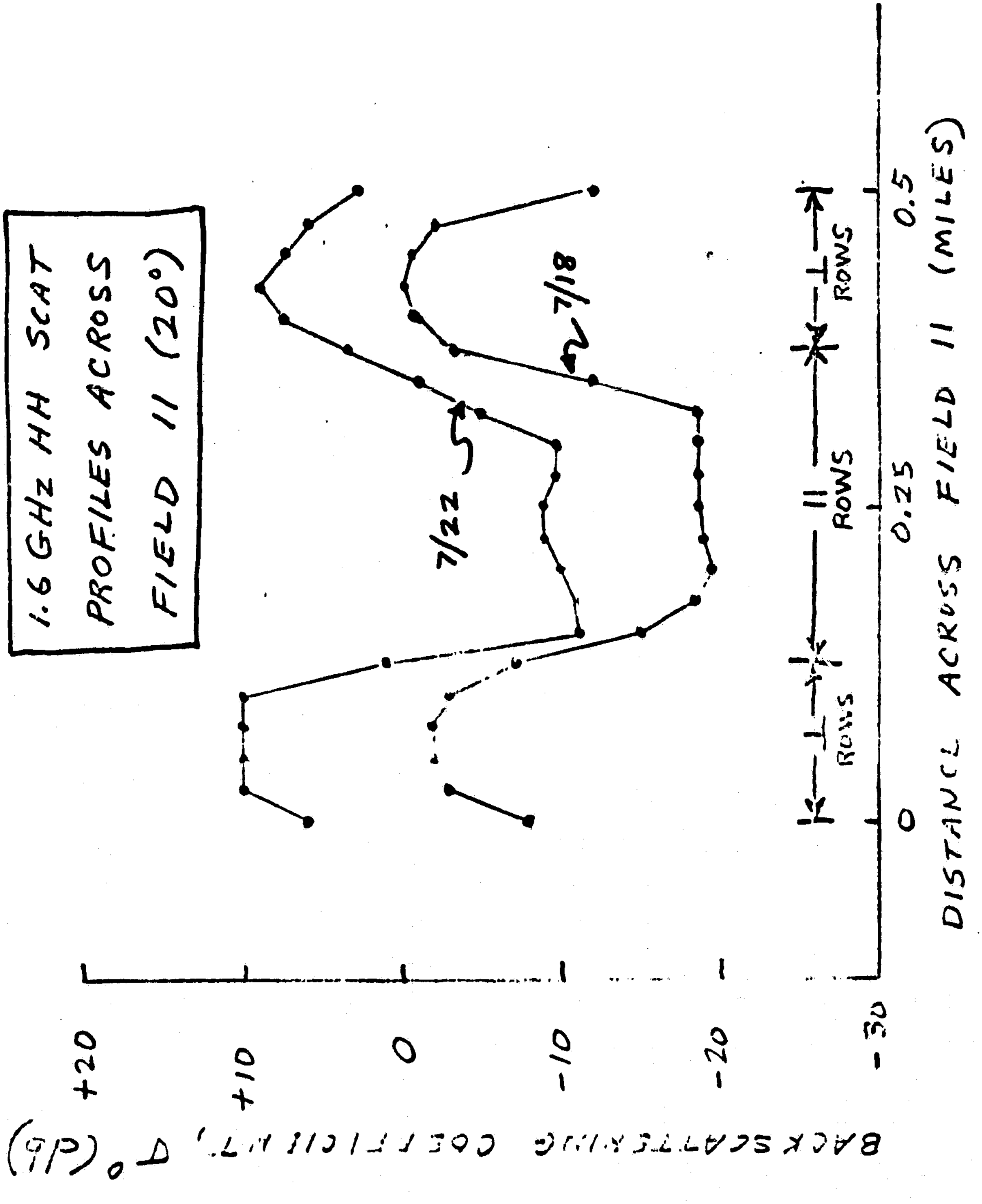

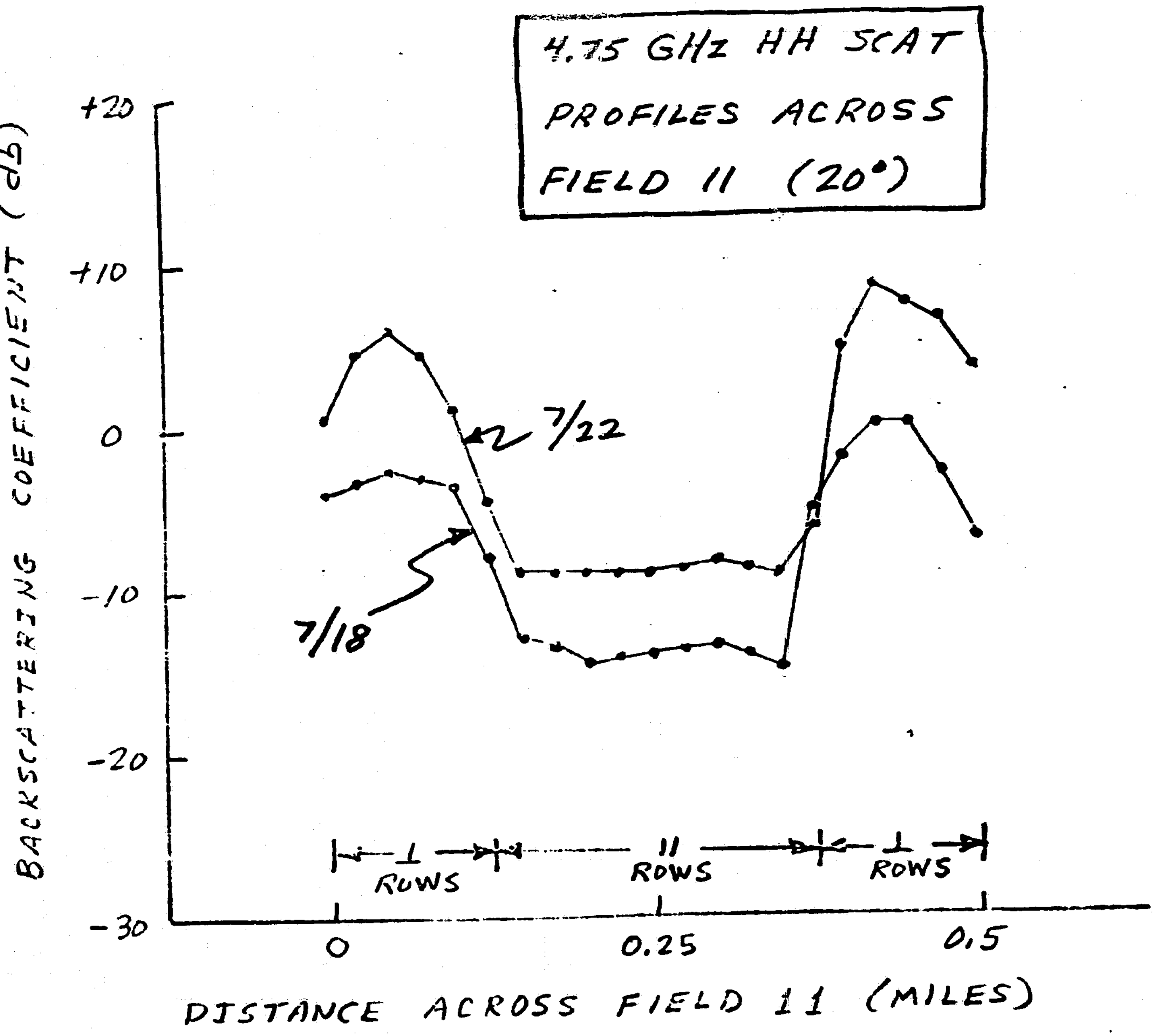
4.75 GHz HH SCAT
PROFILES ACROSS
FIELD 11 (20°)
BACKSCATTERING COEFFICIENT (dB)
+20
+10
0
-10
-20
-30
7/22
7/18
1 ROWS
11 ROWS
1 ROWS
0
0.25
0.5
DISTANCE ACROSS FIELD 11 (MILES)

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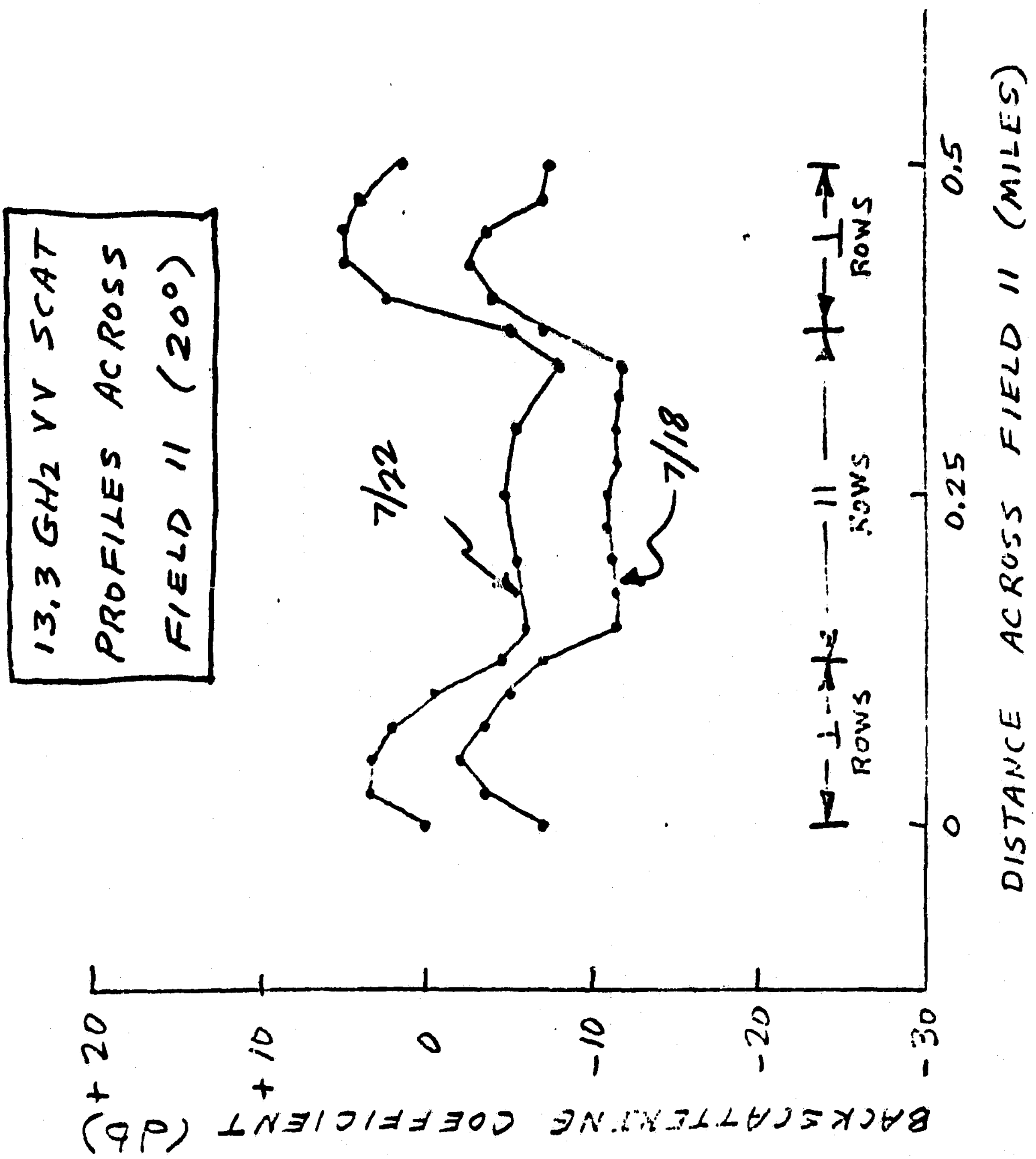

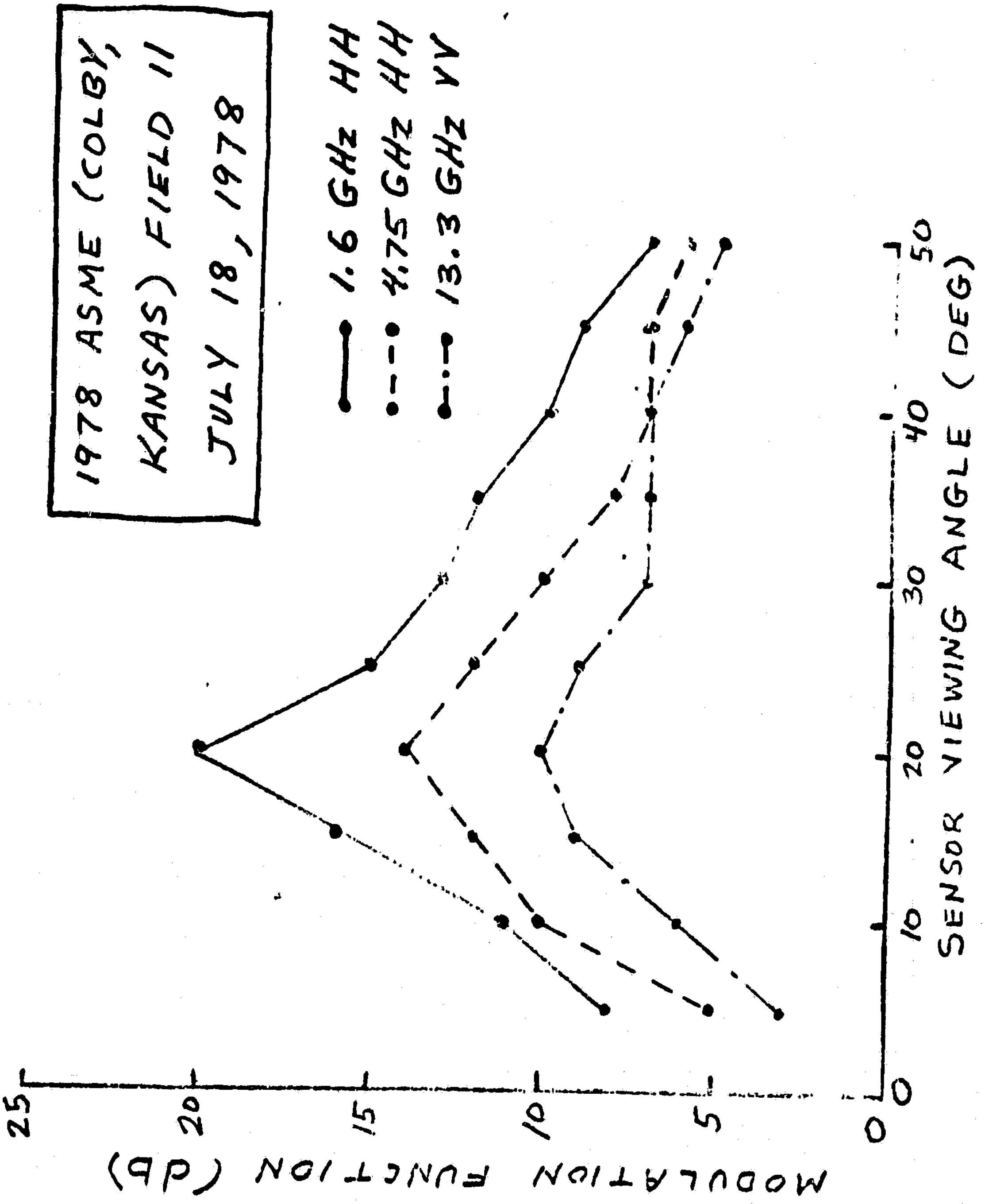
1978 ASME (COLBY, KANSAS) FIELD 11
JULY 18, 1978
1.6 GHz HH
4.75 GHz HH
13.3 GHz VV
MODULATION FUNCTION (dB)
SENSOR VIEWING ANGLE (DEG)
0
5
10
15
20
25
0
10
20
30
40
50

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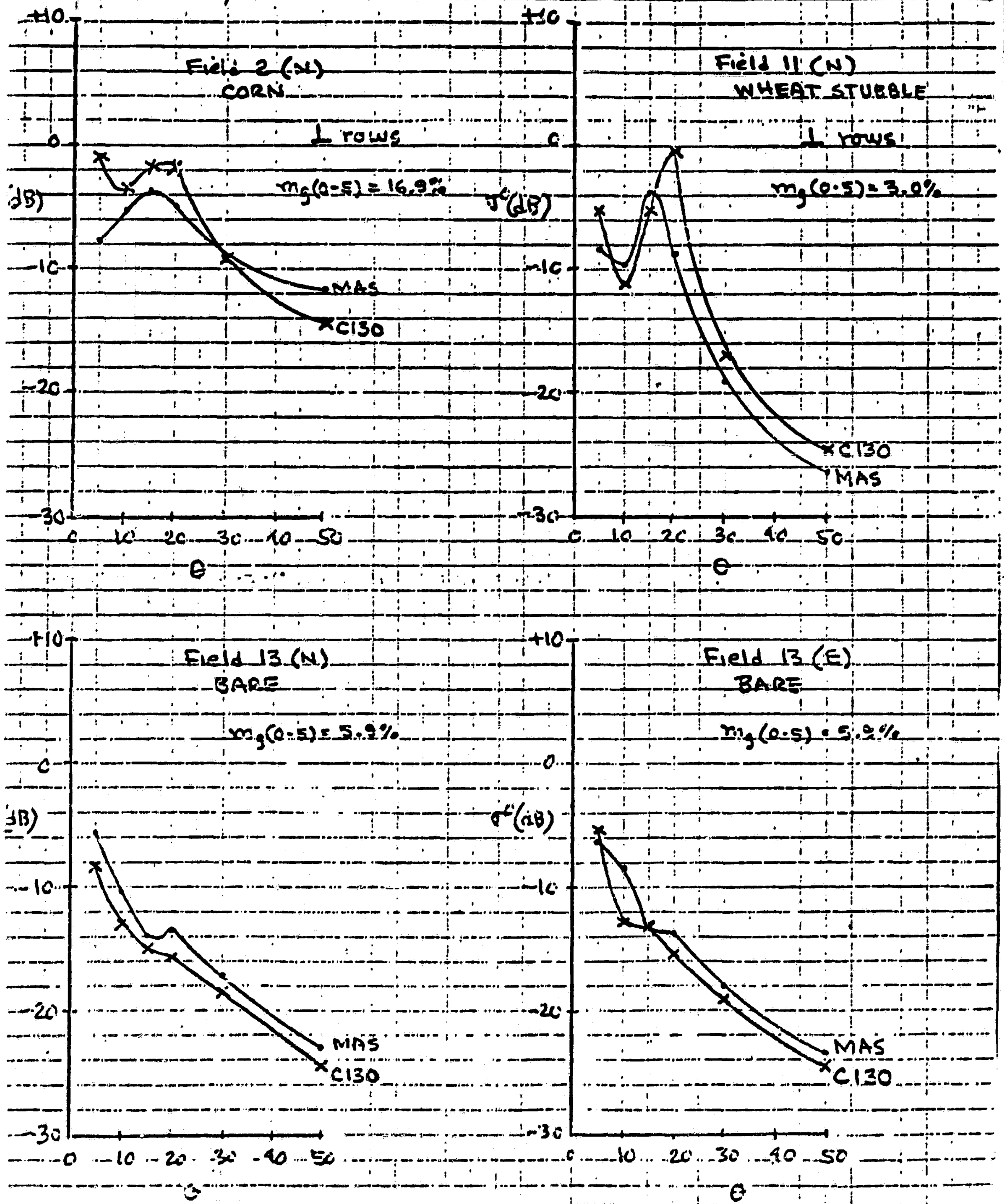
σ^o vs θ 1.6 GHz HH Flight 1 7/18/78



INFORMATION EXTRACTION ANALYSES (E4/T1)

OBJECTIVE (PIP): INTEGRATE TECHNICAL RESULTS OF UNIVERSITY EFFORTS TO DEVELOP CANDIDATE MULTISENSOR SOIL MOISTURE EXTRACTION ALGORITHMS AND TO ASSESS ACCURACY OF THESE ESTIMATES

ACTIVITIES:

- MERGED MODEL DEVELOPMENT
    - SOIL MOISTURE PROFILE (FY80-82)
    - SOIL TEMPERATURE PROFILE (FY80-82)
    - RADIATIVE TRANSFER (IR, MW, PASSIVE, ACTIVE) (FY80-82)
        - DIELECTRIC CONSTANT MODELS (FY80)
        - ROUGHNESS MODELS (FY81-82)
        - RADIATIVE TRANSFER IN SOIL (FY80)

SOIL MOISTURE PROFILE MODELS

o PALMER	--TWO LAYER, GENERAL CROPLAND
o VSMB (B&R)	--SIX LAYERS, SEVERAL SOIL & PLANT COMBINATIONS, CLIMATE SPECIFIC
o FEYERHERM	--SIMILAR TO VSMB BUT PLANT & SOIL SPECIFIC
o KANEMASU	--SEPARATES EVAPORATION & TRANSPIRATION 5 LAYERS, LOCATION SPECIFIC
o SIMBAL (STUFF)	--10 LAYERS, CORN ON POORLY-DRAINED SOIL
o SAXTON	--FLEXIBLE, RANGE OF SOILS & CROPS SIMPLIFIED SOIL WATER EQUATION FOR WATER MOVEMENT
o HANKS	--LIMITED CROP CAPABILITY, INCLUDES EQUATIONS FOR PHYSICAL PROCESSES OF WATER MOVEMENT
o WATBAL 1 (VAN BAVEL)	--FLEXIBLE, GENERAL, USES CSMP III INCLUDES EQUATIONS FOR WATER MOVEMENT

SENSITIVITY OF EXISTING YIELD MODELS (KSU)

OBJECTIVE (SOW): TO ASSESS THE IMPROVEMENT IN PREDICTIVE (ESTIMATION) CAPABILITY OF YIELD MODELS INCORPORATING SOIL MOISTURE MODELS AND/OR MEASUREMENTS WITH METEOROLOGICAL INFORMATION VS. YIELD MODELS UTILIZING ONLY METEOROLOGICAL INFORMATION (TEMPERATURE AND PRECIPITATION)

ACTIVITIES:

- JAN 24-25, 1980 WORKSHOP AT KSU
- DRAFT OF POSITION PAPER (MAR 1, 1980)
- FINAL POSITION PAPER (JUL 1, 1980)
- ANALYSES OF YIELD MODELS (APR 1 - AUG 1, 1980)

APPENDIX E
PRESENTATION BY ENI NJOKU

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JOINT MICROWAVE AND INFRARED STUDIES FOR SOIL MOISTURE DETERMINATION

Quantitative soil moisture measurements on a global basis are essential for planning and modeling in agriculture, climatology, and hydrology. A major part of the soil moisture information is currently used for these purposes is derived from measurements of precipitation. These precipitation measurements, in general, do not provide sufficient coverage and are not uniquely correlated to soil moisture content. With the spatial and temporal coverage requirements, it would be highly desirable to obtain soil moisture information from satellites. A likely candidate for a sensor system to measure soil moisture from space combines passive microwave and thermal IR detectors. It is now possible to orbit large microwave antennas which can provide sufficient surface resolution at the lower frequencies to enable meaningful measurements of soil moisture content to be made. Thermal infrared data can be obtained simultaneously to improve the soil moisture determination algorithms.

The potential of microwave radiometry for soil moisture sensing lies in the marked increase in the dielectric constant of wet soil over that of dry soil, due to the presence of moisture. The resultant decrease in emissivity leads to a pronounced decrease in the microwave brightness temperature which is measurable by remote sensors. This has been confirmed in the past by a series of ground-based and aircraft measurements which show an approximately linear decrease in brightness temperature as a function of increasing moisture content. These measurements exhibit a rather large scatter, however, due to the numerous other surface features which also affect the microwave emission.

This study is an attempt to better quantify the effects of these surface features such as variations in the moisture and temperature profiles, subsurface layering, surface roughness, and vegetation cover. Theoretical models have been developed starting on a simple basis, and are being extended to account for the significant features found in natural terrain.

The microwave brightness temperature is affected by surface temperature as well as the other surface characteristics discussed above. Thus, surface temperature measurements by thermal infrared will improve the soil moisture determination accuracy of a microwave instrument alone. Furthermore, an indication of the soil thermal inertia made possible by such infrared measurements provides additional information on the moisture content. A coupled soil heat and moisture flux model has been developed to aid in interpretation of the infrared data. A major objective of this study is to examine the interrelationships between the microwave and infrared models, and ultimately to derive algorithms for retrieving near-surface soil moisture information from combined microwave and infrared remotely-sensed data sets.

Field experiments have been undertaken in the southern San Joaquin Valley, California, to acquire data to enable verification and improvement of both microwave and thermal-moisture models. Data were obtained using microwave and infrared ground-based systems. The test sites consisted of bare fields with the capability of being ploughed, irrigated, and instrumented at will. The field work was undertaken in cooperation with Dr. John Estes, S. Atwater, P. O'Neill, and other students of the Geography Remote Sensing Unit, U. C. Santa Barbara. Measurements with the microwave radiometric system - consisting of UHF (0.6 to 0.9 GHz/50.0 to 33.3 cm), L band (1.42 GHz/21.4 cm), and X band (10.69 GHz/2.8 cm) channels - were made at horizontal and vertical polarizations as functions of view angle, soil moisture and temperature conditions, and surface roughness. Measurements of surface thermal infrared emission were made from 8 to 14 μm.

Soil samples were obtained at frequent intervals during the experiment for analysis in terms of moisture content, bulk density, and texture. Temperature probes were used at various depths to monitor the changing temperature profiles. The net result was a complete set of subsurface temperature and moisture profiles as a function of time during the course of the experiment.

Measurements of the micrometeorological conditions in the lower (surface) boundary layer were also made.

This report describes the two modeling efforts, the data acquisition and interpretation, and future plans for combining measurements and models of the two spectral regions into a valid soil moisture measurement technique.

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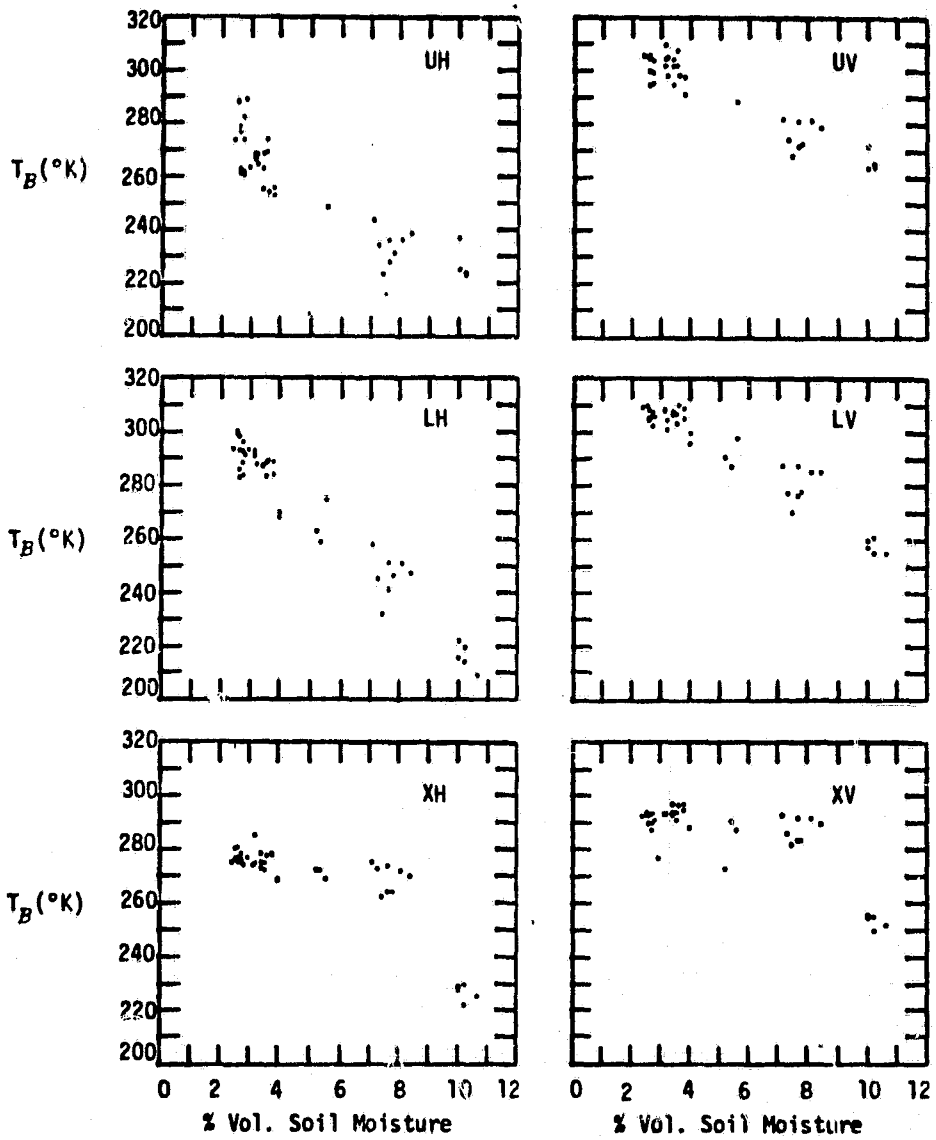
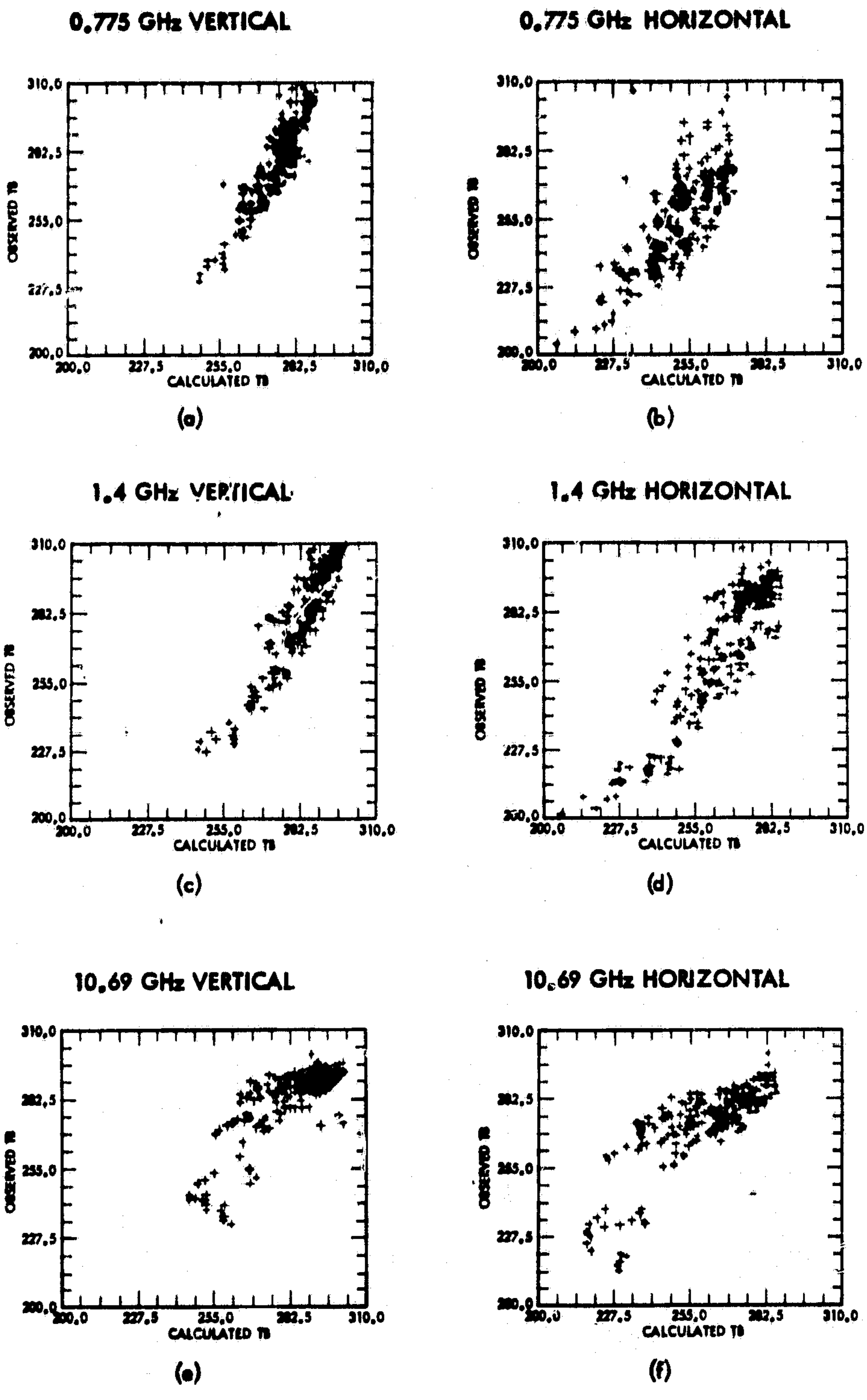
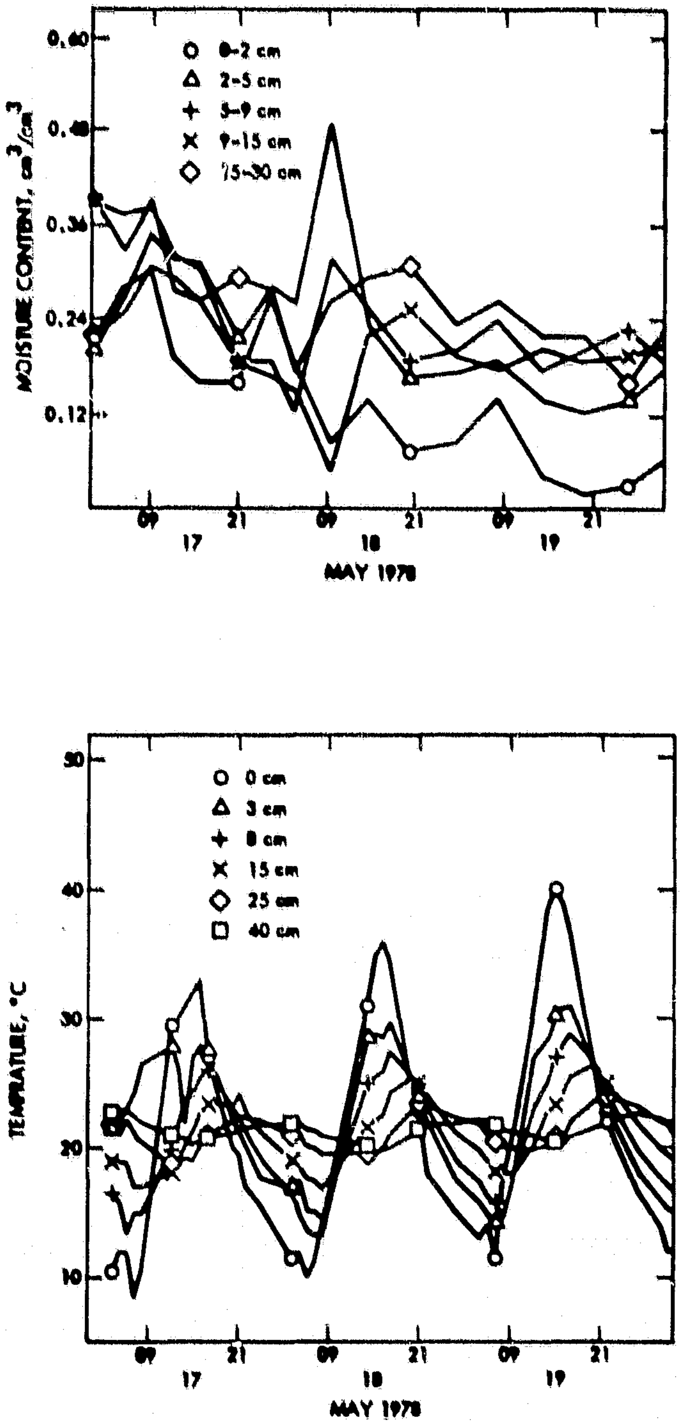
1979 Rough Plot
Microwave T_B vs. 0-2 cm. Volumetric Soil Moisture
45° Look Angle



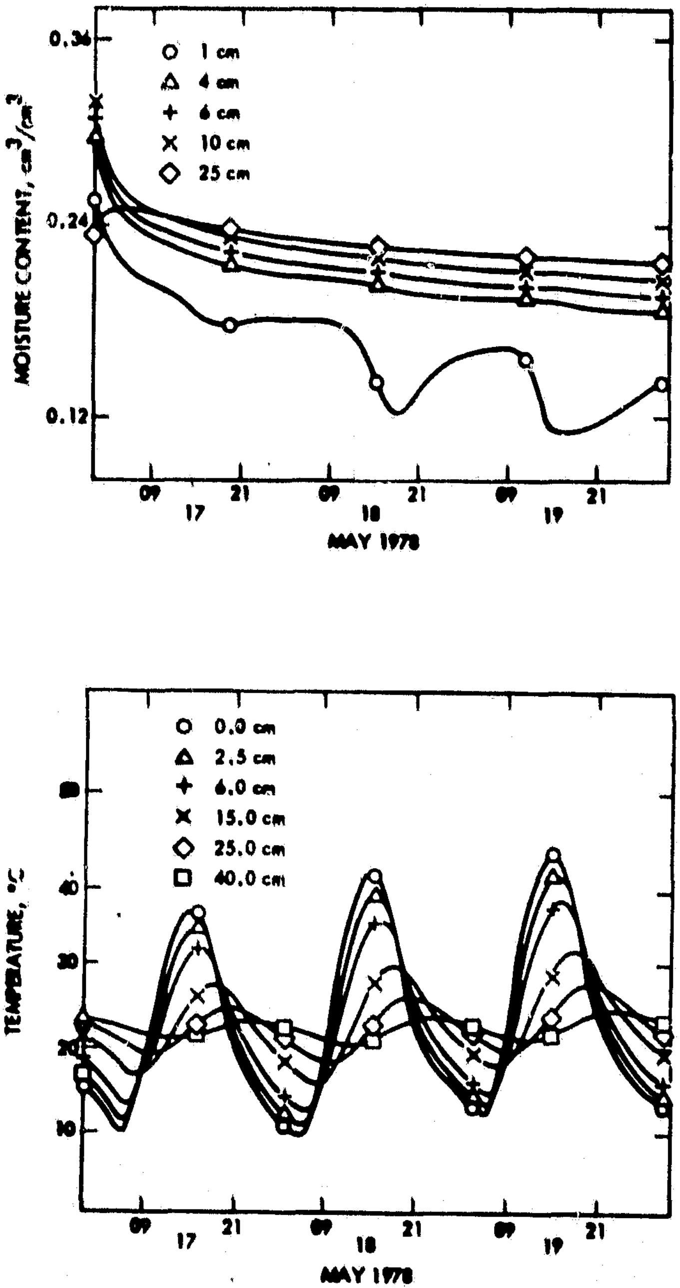
Brightness temperature vs. soil moisture content in the top 0-2 cm at 45° viewing angle (U = .775 GHz, L = 1.43 GHz, X = 10.69 GHz).



Observed vs. calculated brightness temperatures for the 1979 data set (25°, 35° and 45° viewing angles; 14° to 48°C surface temperature range).



Soil moisture and temperature variations at different depths, measured during the 1978 field experiment.



Soil moisture and temperature variations for the 1978 experiment computed using the JPL heat and moisture flux model.

APPENDIX F
PRESENTATION BY BILL WAITE AND DON SCOTT
UNIVERSITY OF ARKANSAS

AGRISTARS
SOIL MOISTURE PROJECT
EVALUATION WORKSHOP
BELTSVILLE AGRICULTURAL RESEARCH CENTER
JUNE 16-17, 1980

REMOTE SENSING OF SOIL MOISTURE MEASUREMENT AND ANALYSIS

W. P. WAITE
H. D. SCOTT

DEPARTMENT OF ELECTRICAL ENGINEERING
DEPARTMENT OF AGRONOMY
UNIVERSITY OF ARKANSAS
FAYETTEVILLE, ARKANSAS

OBJECTIVE

DEVELOP THE CAPABILITY TO REMOTELY SENSE THE SOIL MOISTURE DEPTH PROFILE IN A FASHION COMPATIBLE WITH USE IN AGRICULTURAL CROP YIELD PREDICTION MODELS.

PROCEDURE

MODIFY TRADITIONAL SOIL PHYSICS, HYDROLOGY, AND AGRONOMY MODELS TO ACCEPT REMOTE SENSING MEASUREMENTS AS A SUPPLEMENT OR REPLACEMENT FOR CONVENTIONAL MEASUREMENTS.

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APPROACH (TASKS)

1. PERFORM THEORETICAL MODELING AND LABORATORY MEASUREMENTS OF REFLECTIVITY FOR SOILS WITH REAL AND ARTIFICIAL THERMAL AND MOISTURE GRADIENTS.

2. PERFORM FIELD MEASUREMENTS OF REFLECTIVITY FOR SOILS WITH NATURAL THERMAL AND MOISTURE GRADIENTS.

3. ANALYZE FIELD AND AIRCRAFT EXPERIMENTAL DATA SETS.

4. CONSTRUCT ALGORITHM FOR ESTIMATING THE SOIL MOISTURE GRADIENT IN THE UPPER PORTION OF THE SOIL PROFILE.

5. PROVIDE SUPPORT FOR AIRCRAFT EXPERIMENTS.

TASK 1

1. LABORATORY MEASUREMENTS PERFORMED FOR LAYERED MEDIA

   A. BURIED PLATE

      - SAND

      - SOIL (CLAY-LOAM)

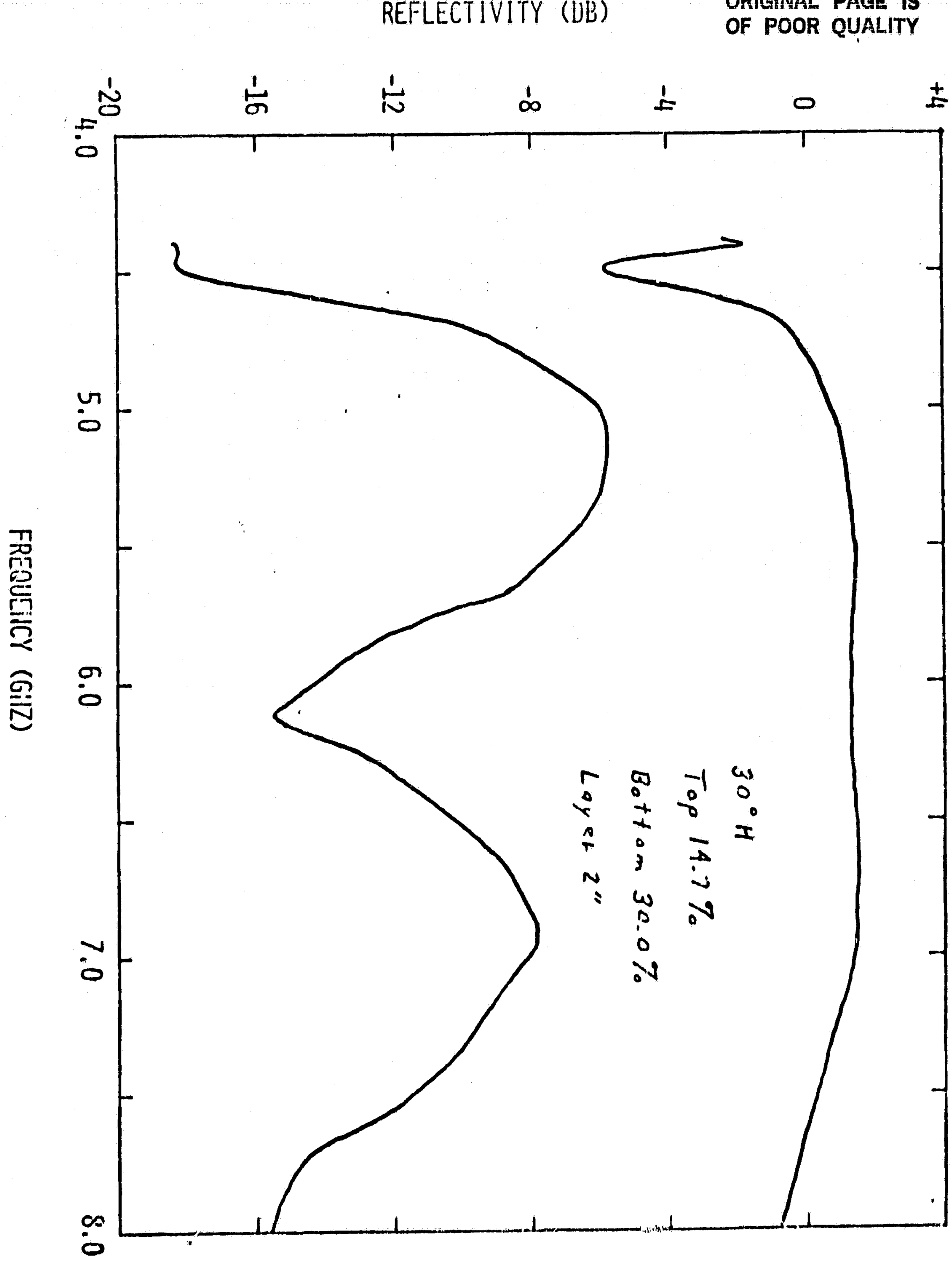
   B. SHARP MOISTURE BOUNDARY

      - SOIL (CLAY-LOAM)

2. RESULTS ACCURATELY PREDICTED BY TWO-LAYER TRANSMISSION LINE MODEL USING TAMU DATA FOR COMPLEX PERMITTIVITY

CONCLUSION

STEP BOUNDARY LAYER MODEL WILL BE IMPOSSIBLE TO INVERT WITH MEASUREMENTS AT MERELY A FEW DISCRETE FREQUENCIES


REFLECTIVITY (DB)
-20
-16
-12
-8
-4
0
+4
4.0
5.0
6.0
7.0
8.0
FREQUENCY (GHZ)
30°H
Top 14.7%
Bottom 30.0%
Layer 2"

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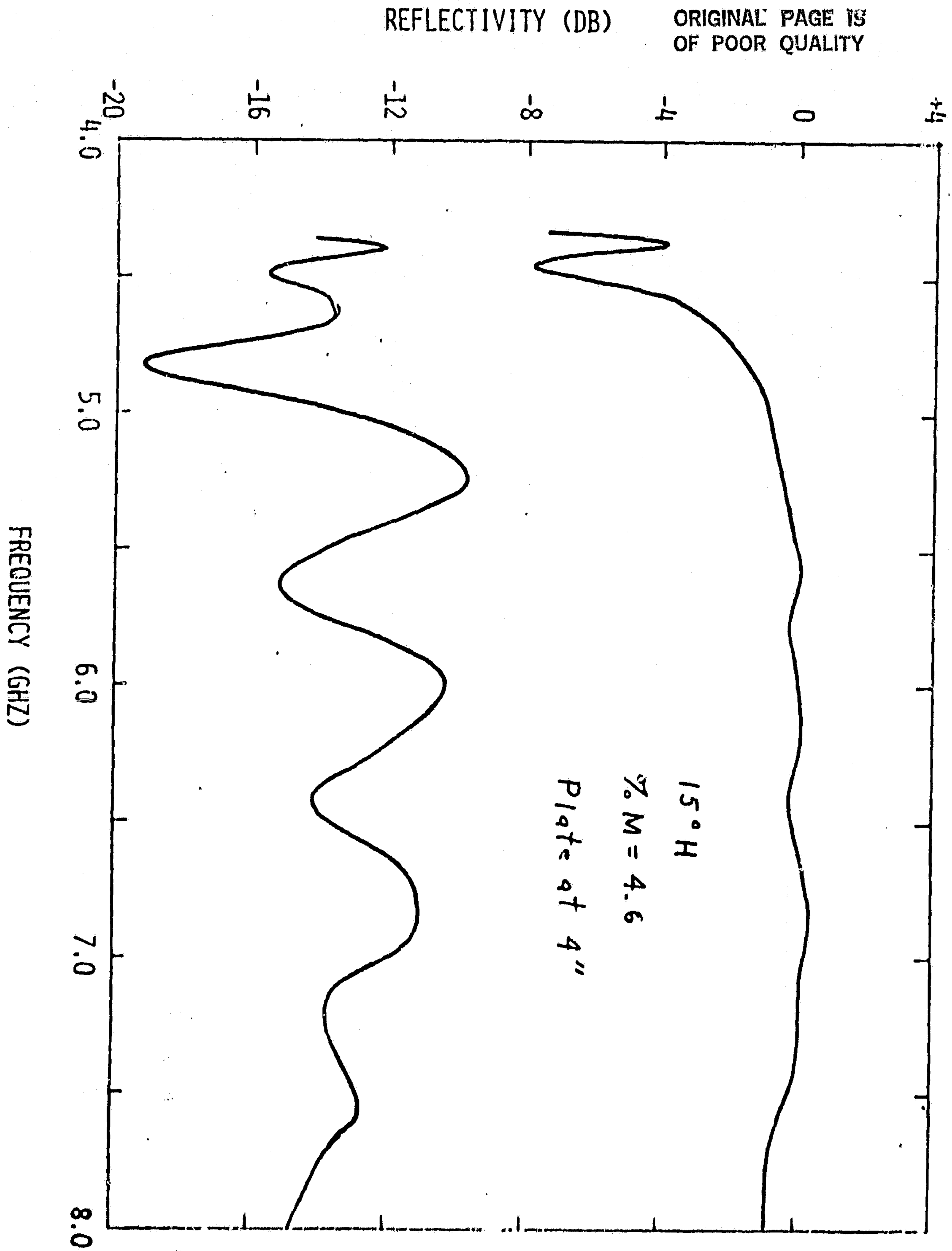

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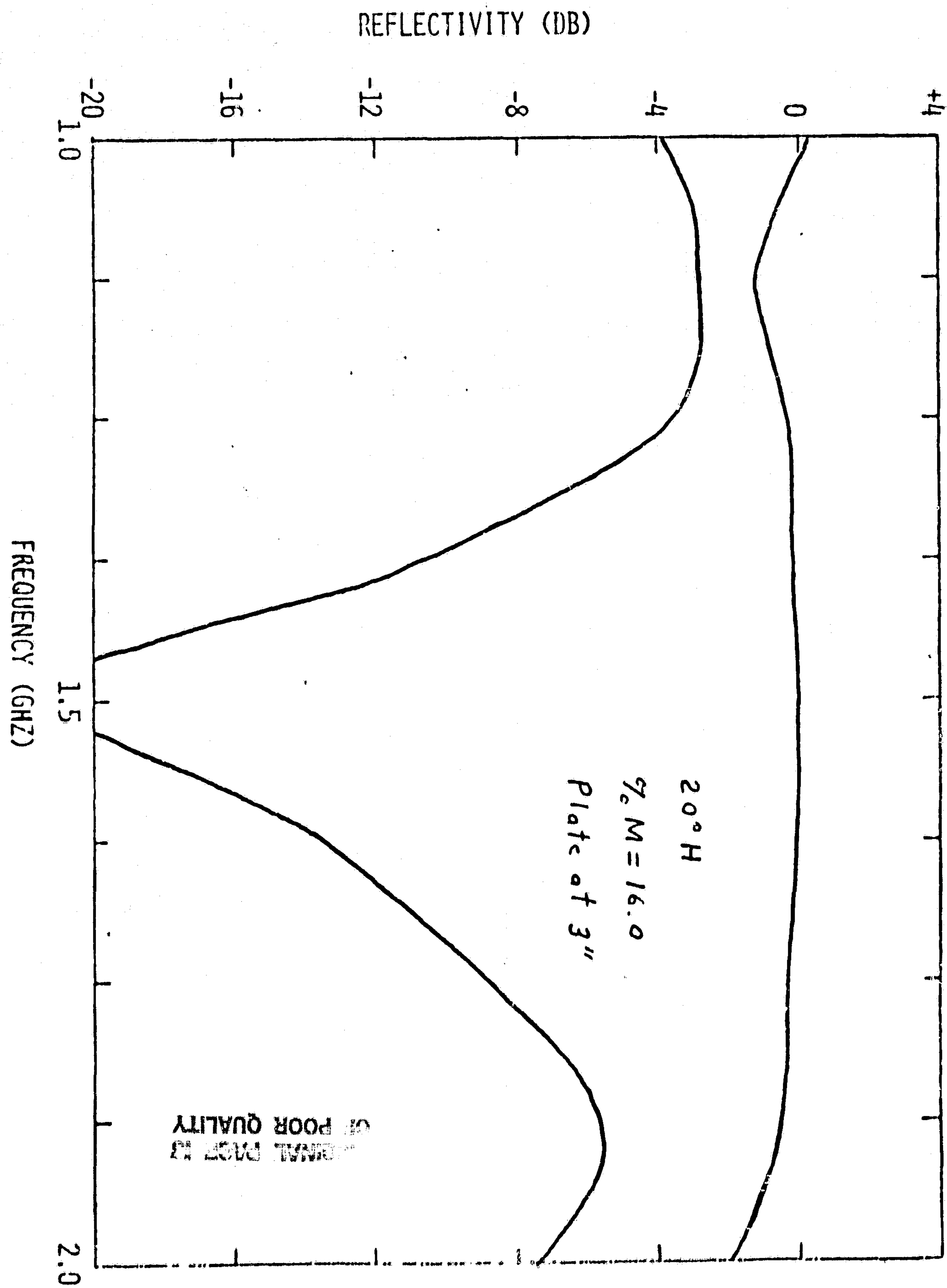
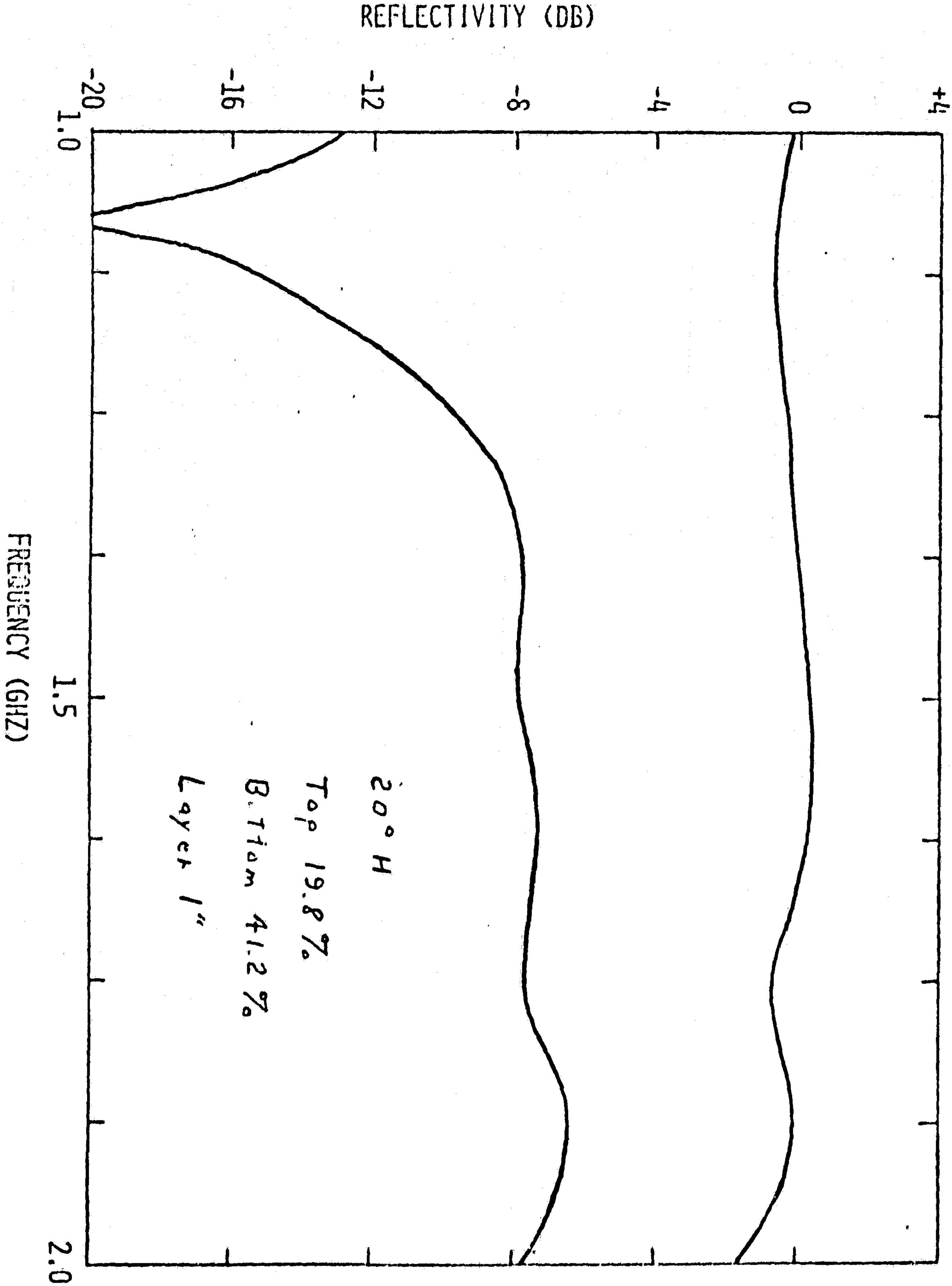
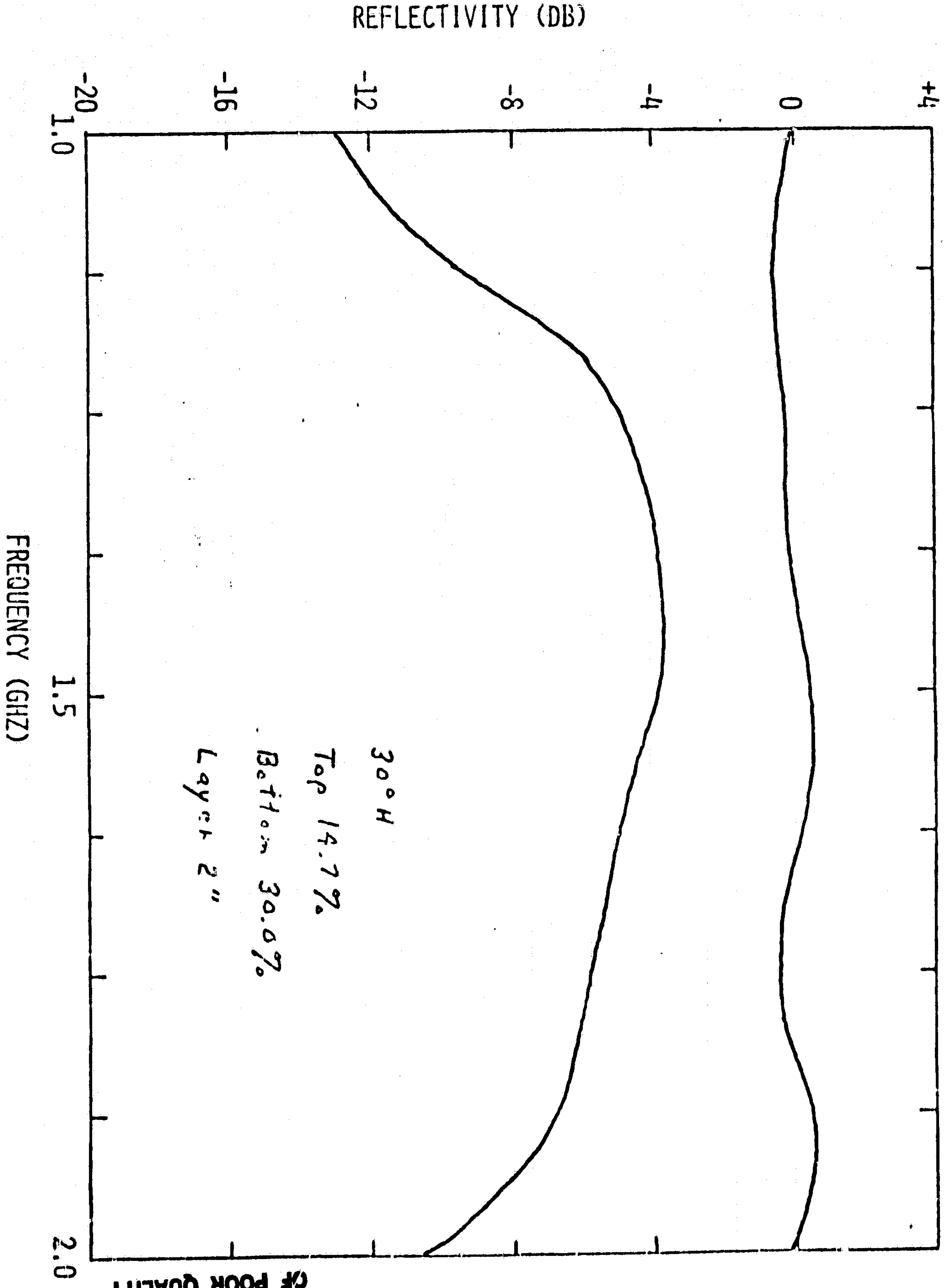

REFLECTIVITY (DB)
+4
0
-4
-8
-12
-16
-20
1.0
1.5
2.0
FREQUENCY (GHZ)
20°H
% M = 16.0
Plate at 3"
OF POOR QUALITY


REFLECTIVITY (DB)
-20
-16
-12
-8
-4
0
+4
1.0
1.5
2.0
FREQUENCY (GHZ)
20° H
Top 19.8%
Bottom 41.2%
Layer 1"


REFLECTIVITY (DB)
+4
0
-4
-8
-12
-16
-20
FREQUENCY (GHZ)
1.0
1.5
2.0
30° H
Top 14.7%
Bottom 30.0%
Layer 2"

TASK 2

PERFORM FIELD MEASUREMENTS OF REFLECTIVITY FOR SOILS WITH NATURAL THERMAL AND MOISTURE GRADKENTS

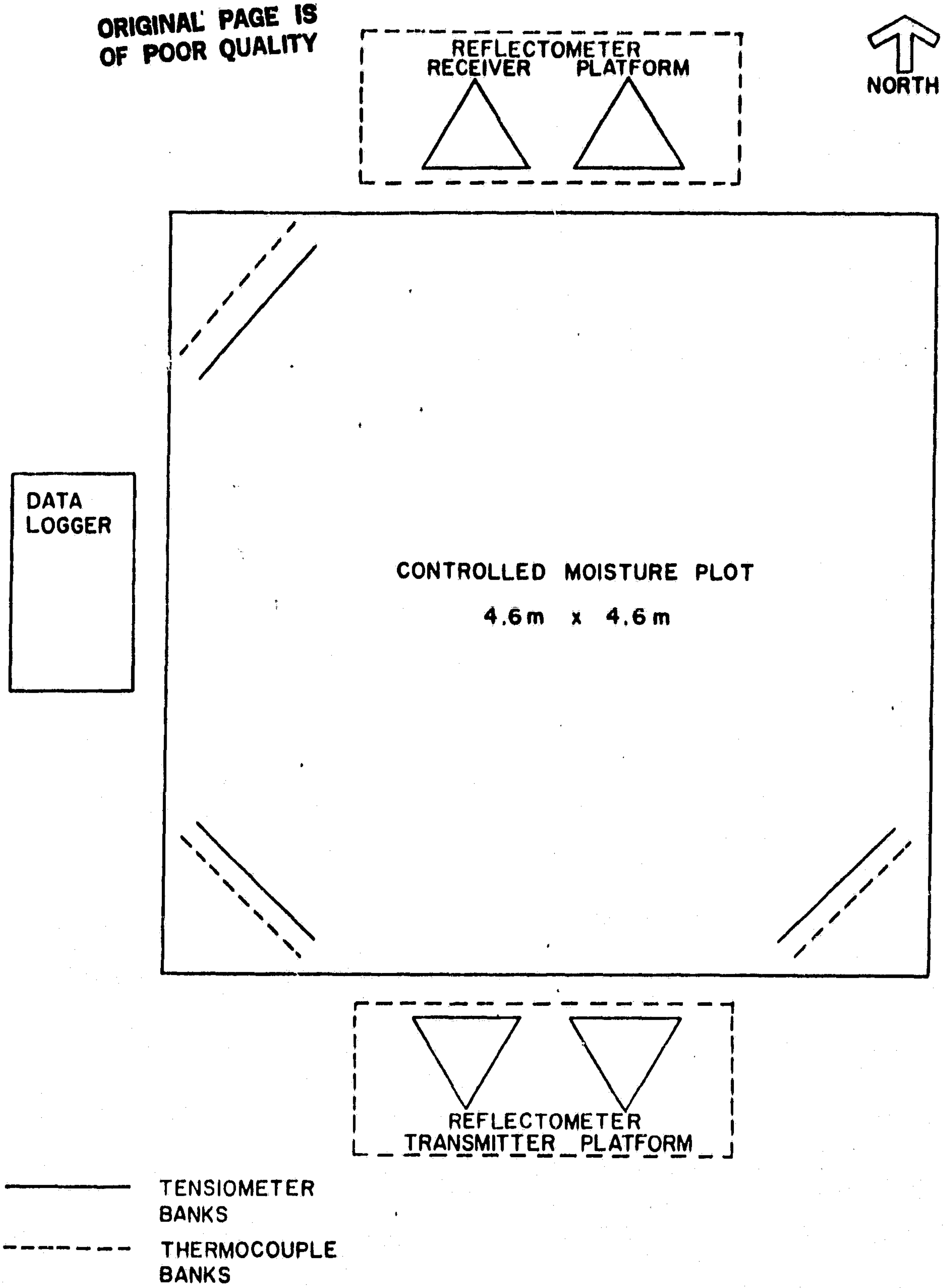


FIGURE 1. INSTRUMENTATION DIAGRAM FOR BOTH NORTH AND SOUTH PLOTS OF THE 1979 BARE SOIL EXPERIMENT AT THE UNIVERSITY OF ARKANSAS

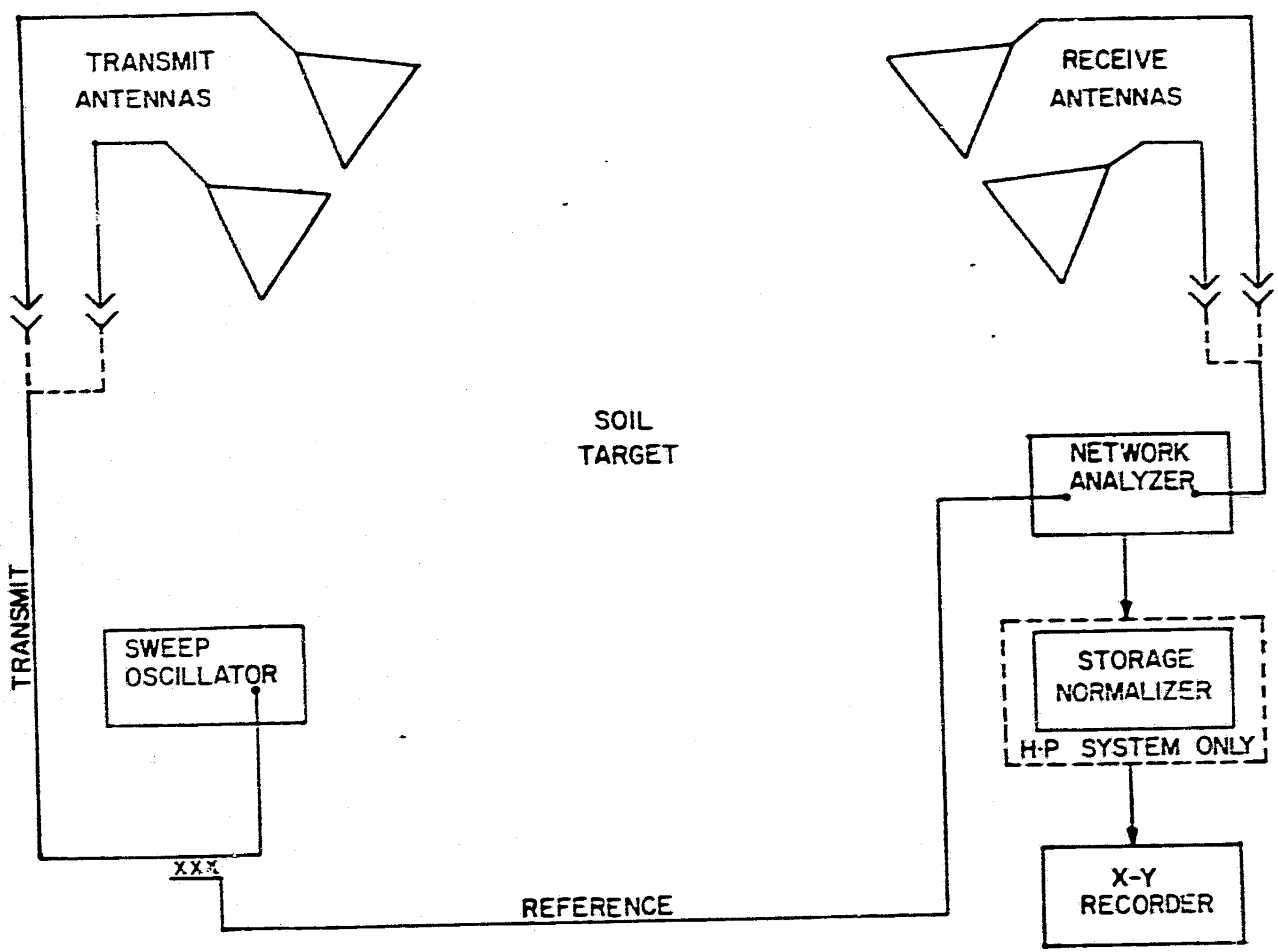


FIGURE 2. BLOCK DIAGRAM OF BISTATIC REFLECTOMETER INTRUMENTATION

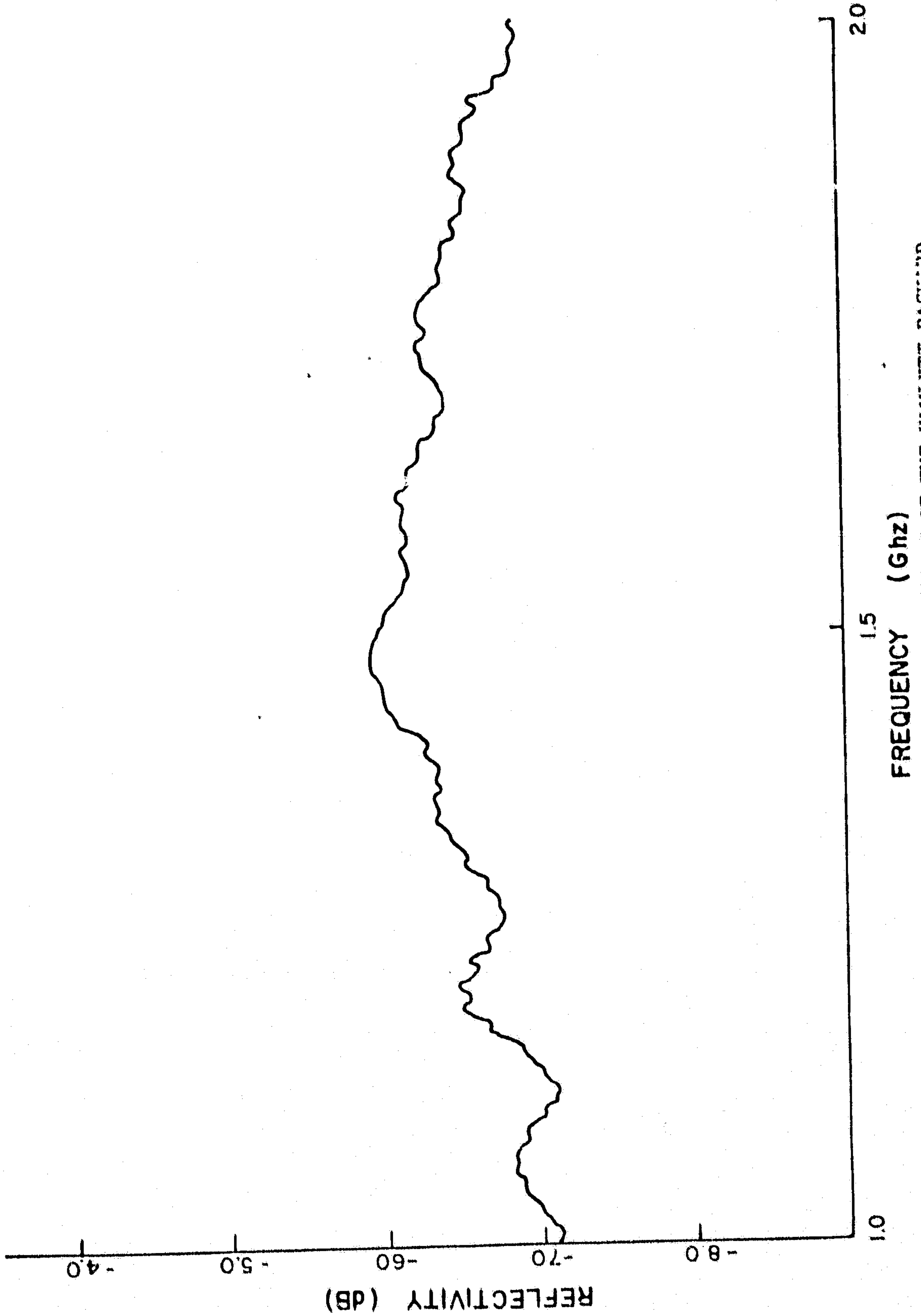


Figure 4. EXAMPLE OF THE RECORDED OUTPUT OF THE HEWLETT-PACKARD NETWORK ANALYZER TAKEN FROM THE DATA OF PLOT 3.

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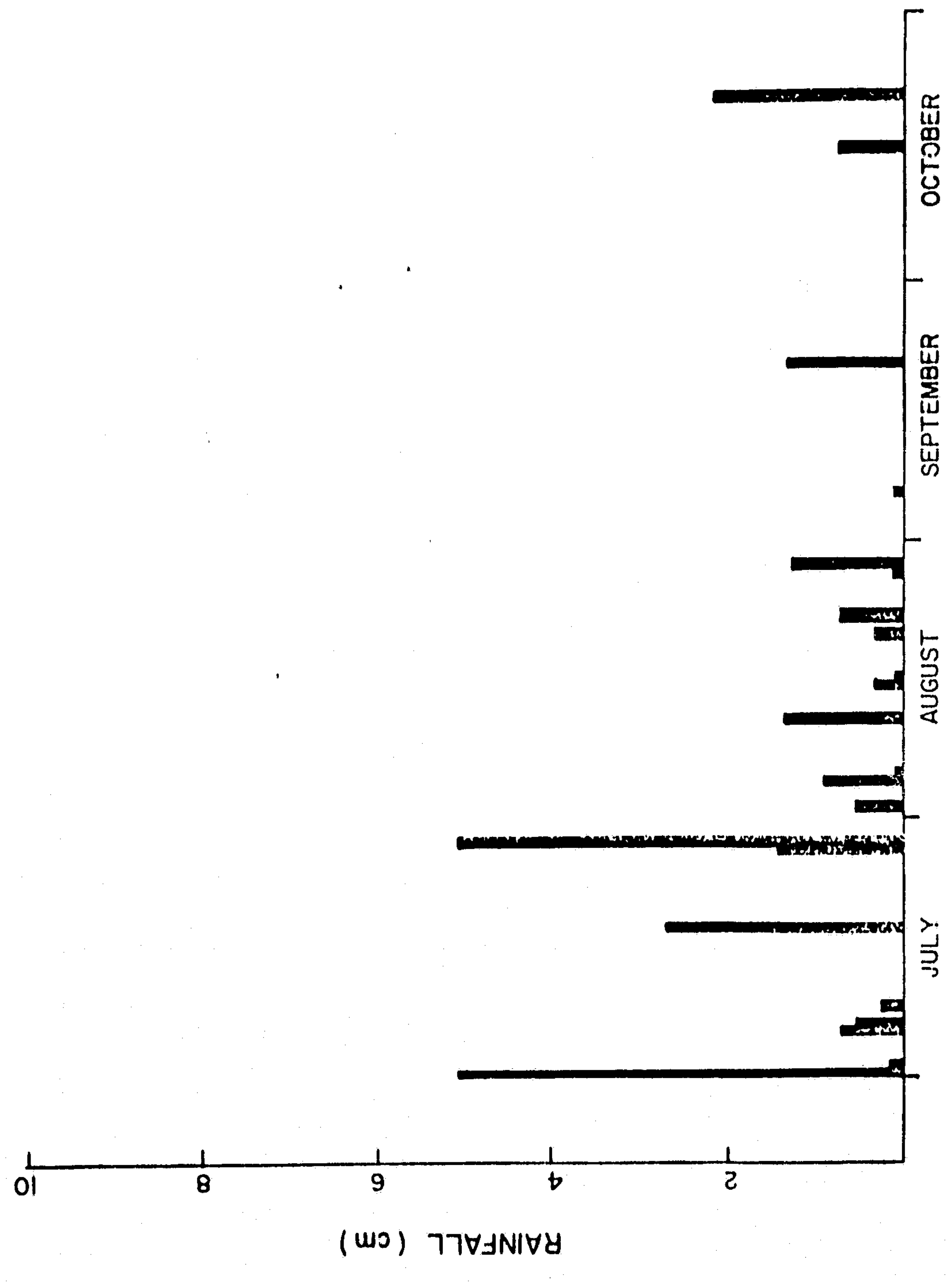

FIGURE 5. GRAPH OF THE SIGNIFICANT RAINFALL DURING THE SUMMER OF 1979

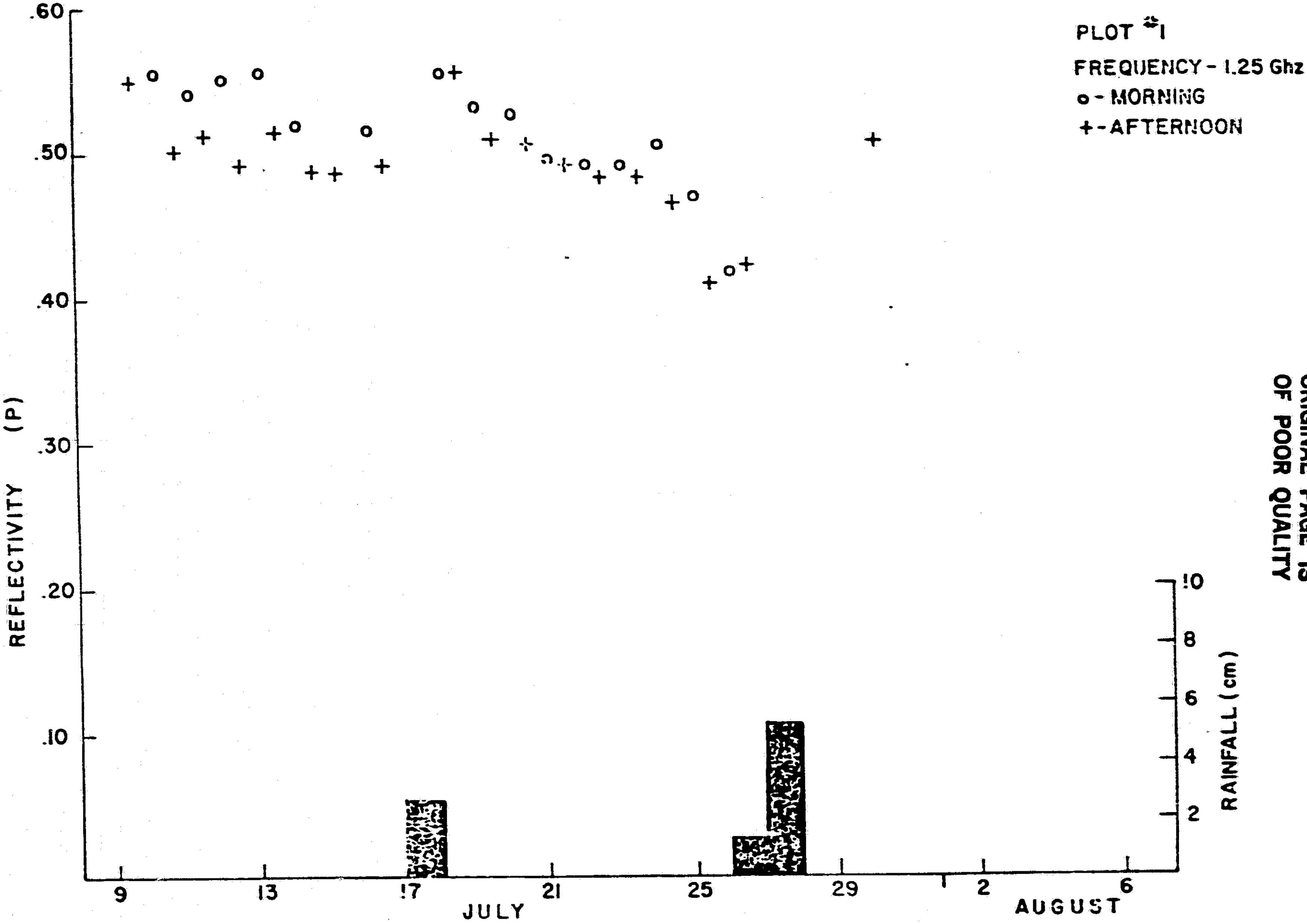

FIGURE 6. 1.25Ghz REFLECTIVITY vs. TIME FOR PLOT 1

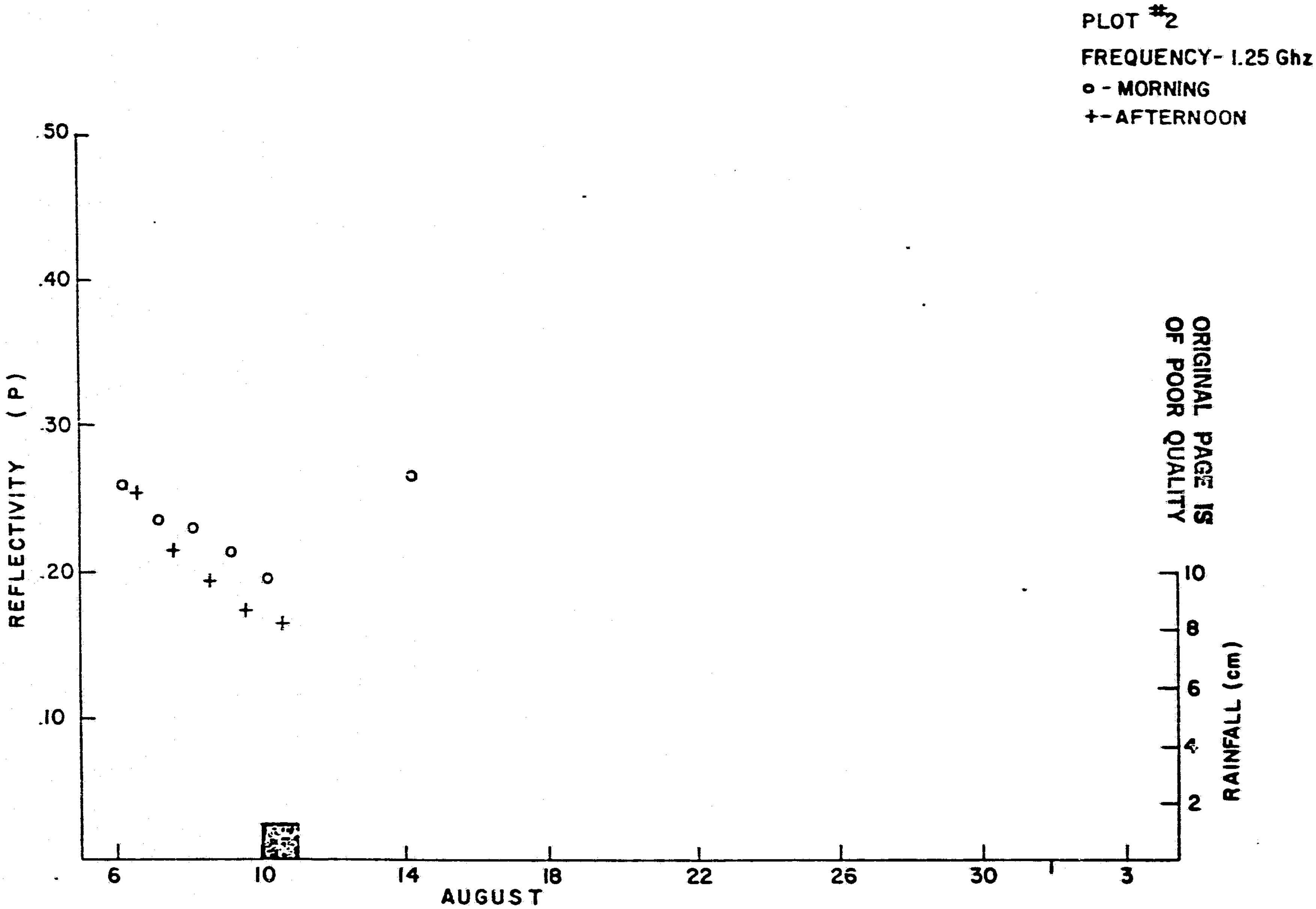

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FIGURE 7. 1.25 Ghz REFLECTIVITY vs. TIME FOR PLOT 2

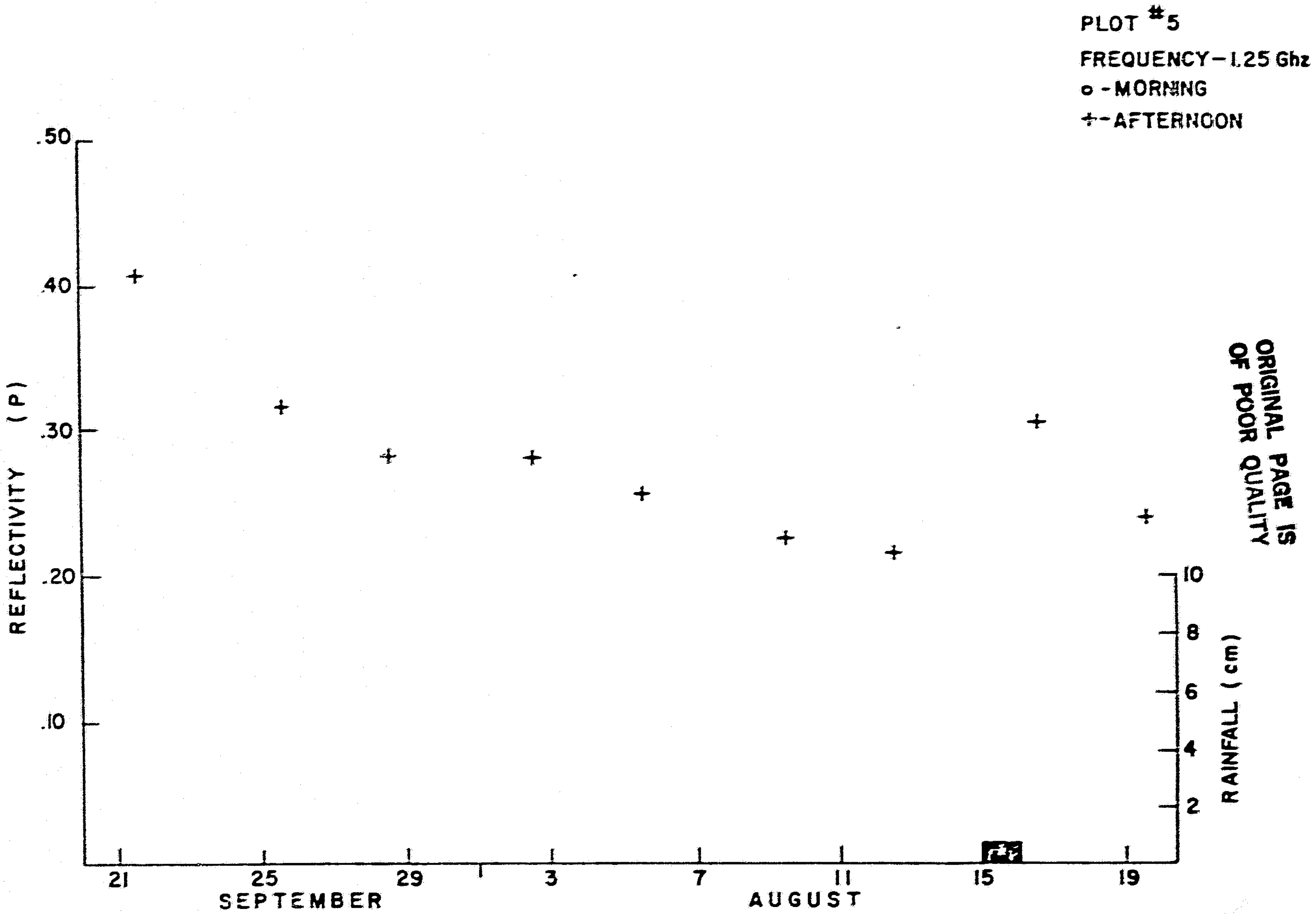
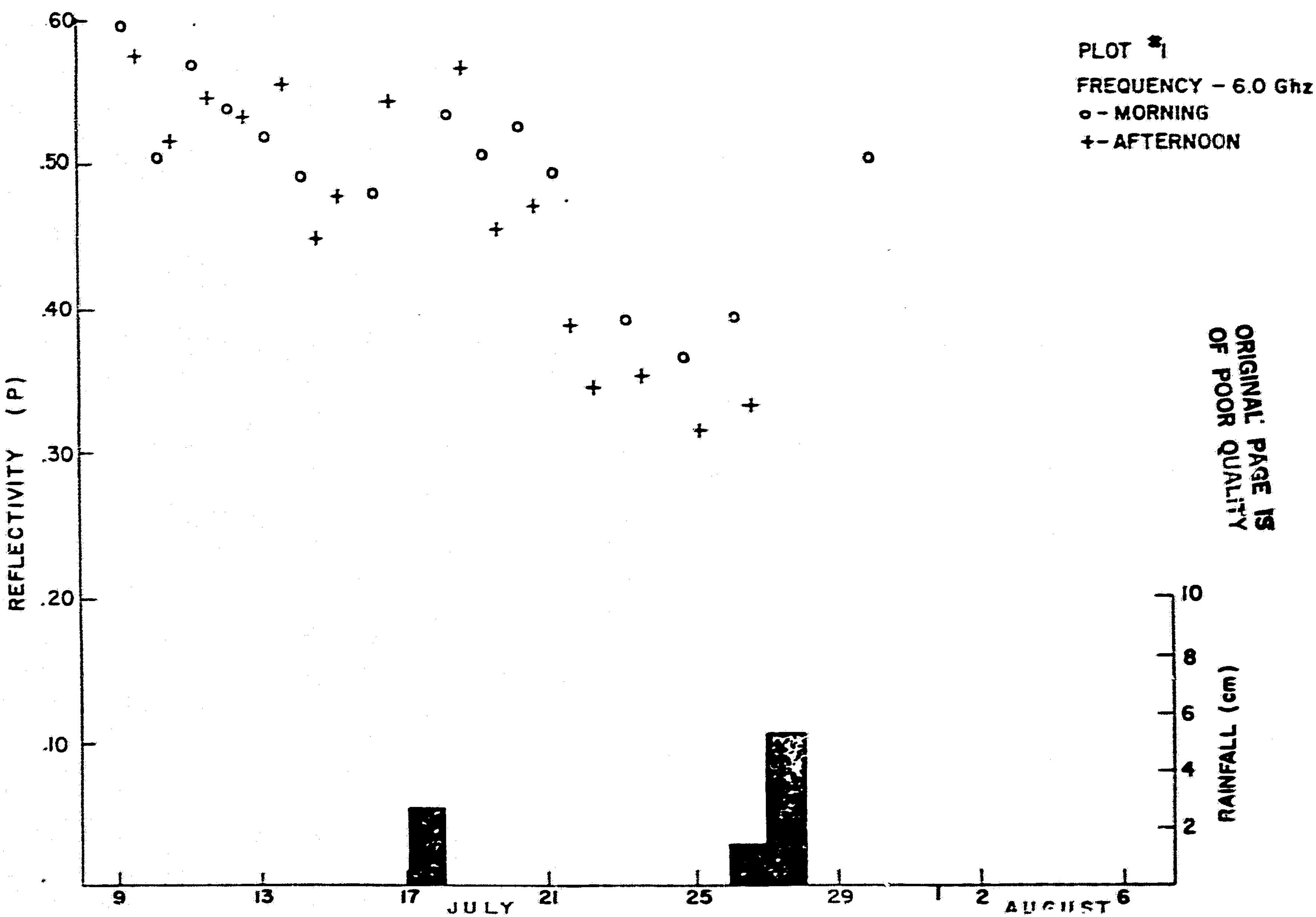


FIGURE 10. 1.25 Ghz REFLECTIVITY vs. TIME FOR PLOT 5


PLOT #1
FREQUENCY – 6.0 Ghz
o – MORNING
+ – AFTERNOON
REFLECTIVITY (P)
.60
.50
.40
.30
.20
.10
RAINFALL (cm)
10
8
6
4
2
9
13
17
JULY
21
25
29
2
AUGUST
6

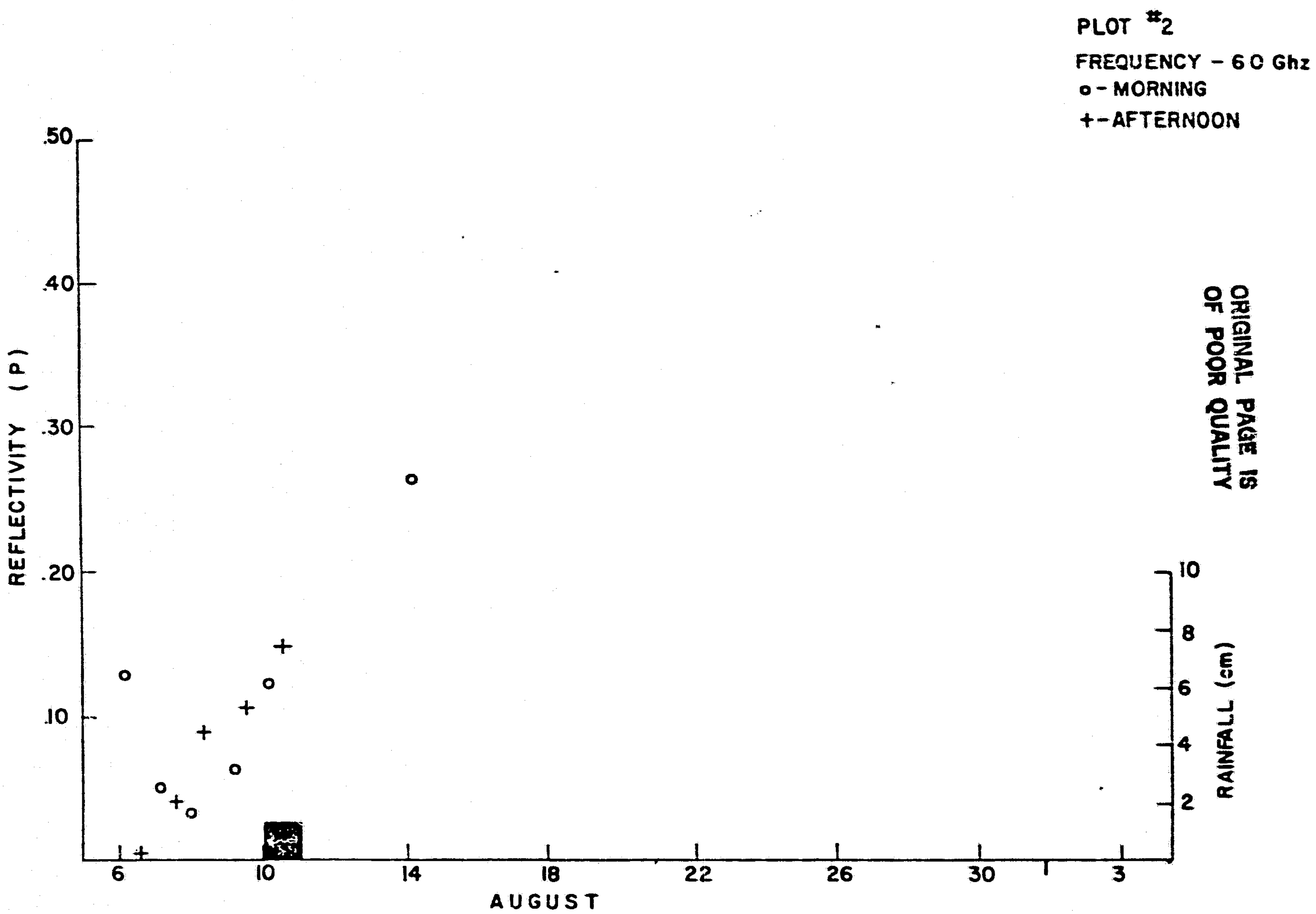


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FIGURE 12. 6.0 Ghz REFLECTIVITY vs. TIME FOR PLOT 2

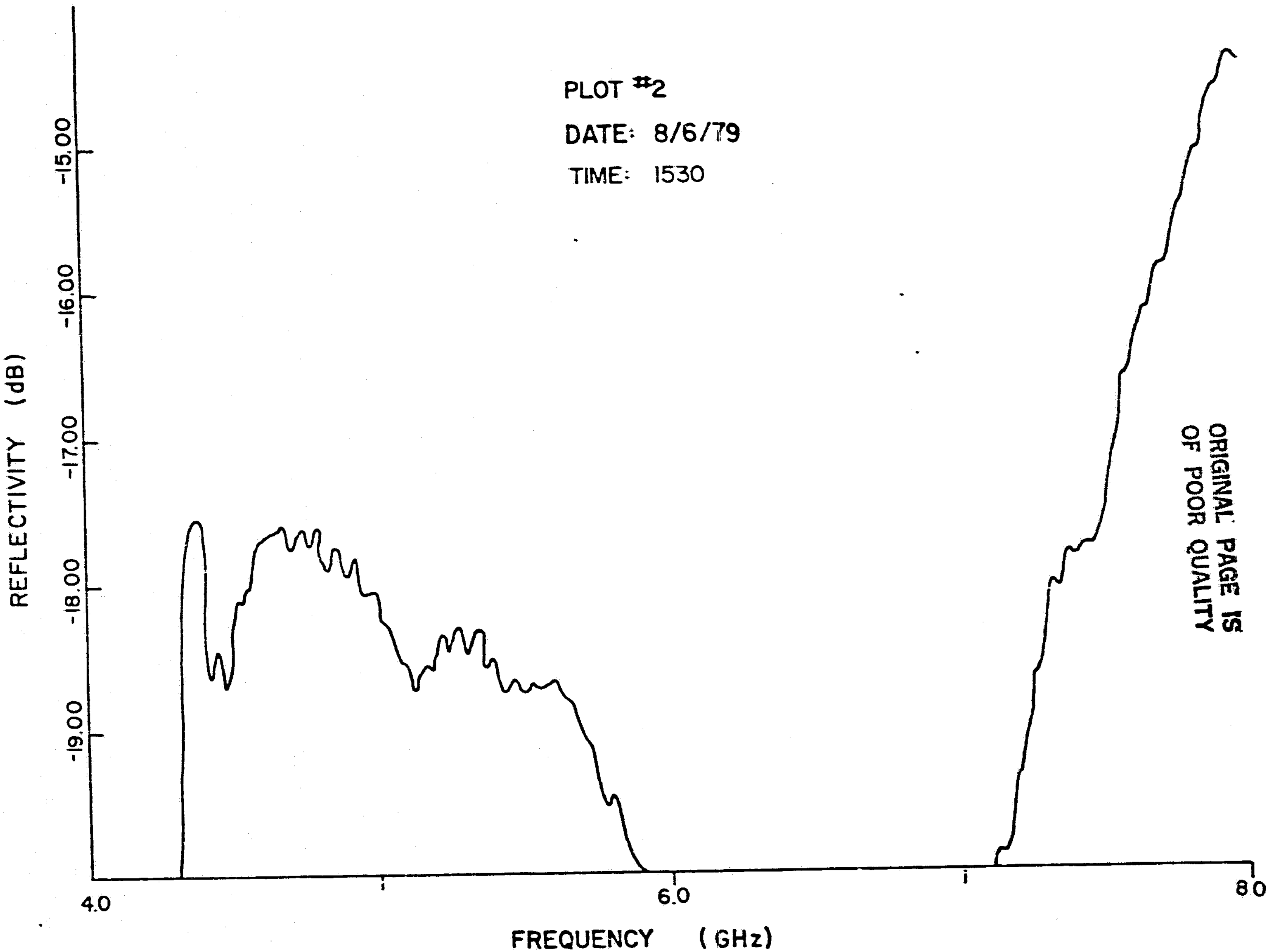

FIGURE 16. EXAMPLE OF MULTI-LAYER EFFECT FOR PLOT 2

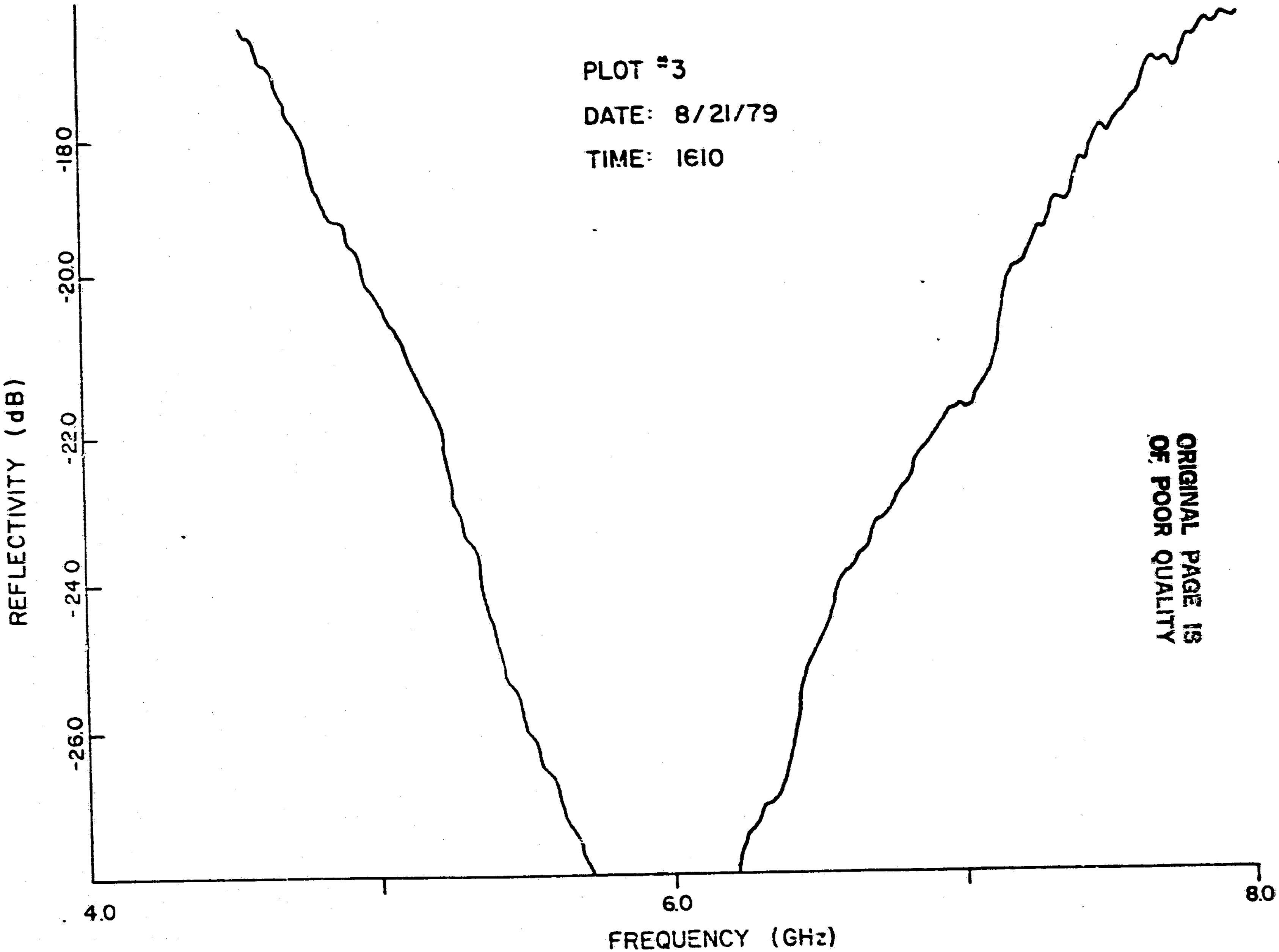

FIGURE 17. EXAMPLE OF MULTI-LAYER EFFECT FOR PLOT 3.

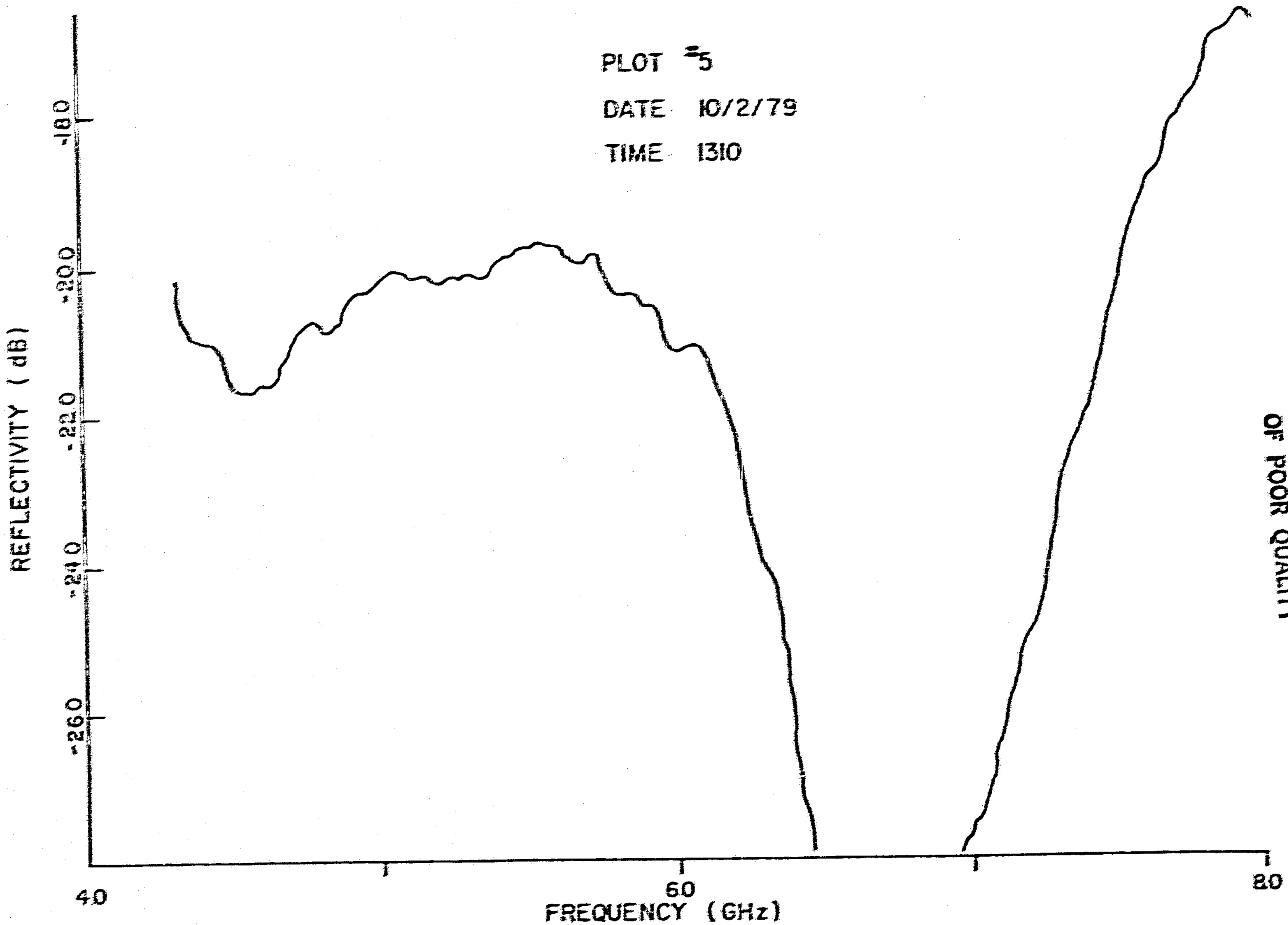

FIGURE 19. EXAMPLE OF MULTI-LAYER EFFECT FOR PLOT 5

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TASK 3

1. CORRELATION ANALYSIS OF AIRBORNE PASSIVE DATA INDICATES

- BRIGHTNESS TEMPERATURE CORRELATES WITH SURFACE LAYER SOIL MOISTURE TO NEAR THE DEGREE PREDICTED BY THE ACCURACY ESTIMATES OF THE GROUND TRUTH MEASUREMENTS

- THE DEPTH OF THE SURFACE LAYER FOR WHICH CORRELATION IS OBTAINED IS FREQUENCY DEPENDENT

- SURFACE ROUGHNESS

    - SMALL SCALE

        - ACTS TO COMPRESS THE SENSITIVITY TO SOIL MOISTURE

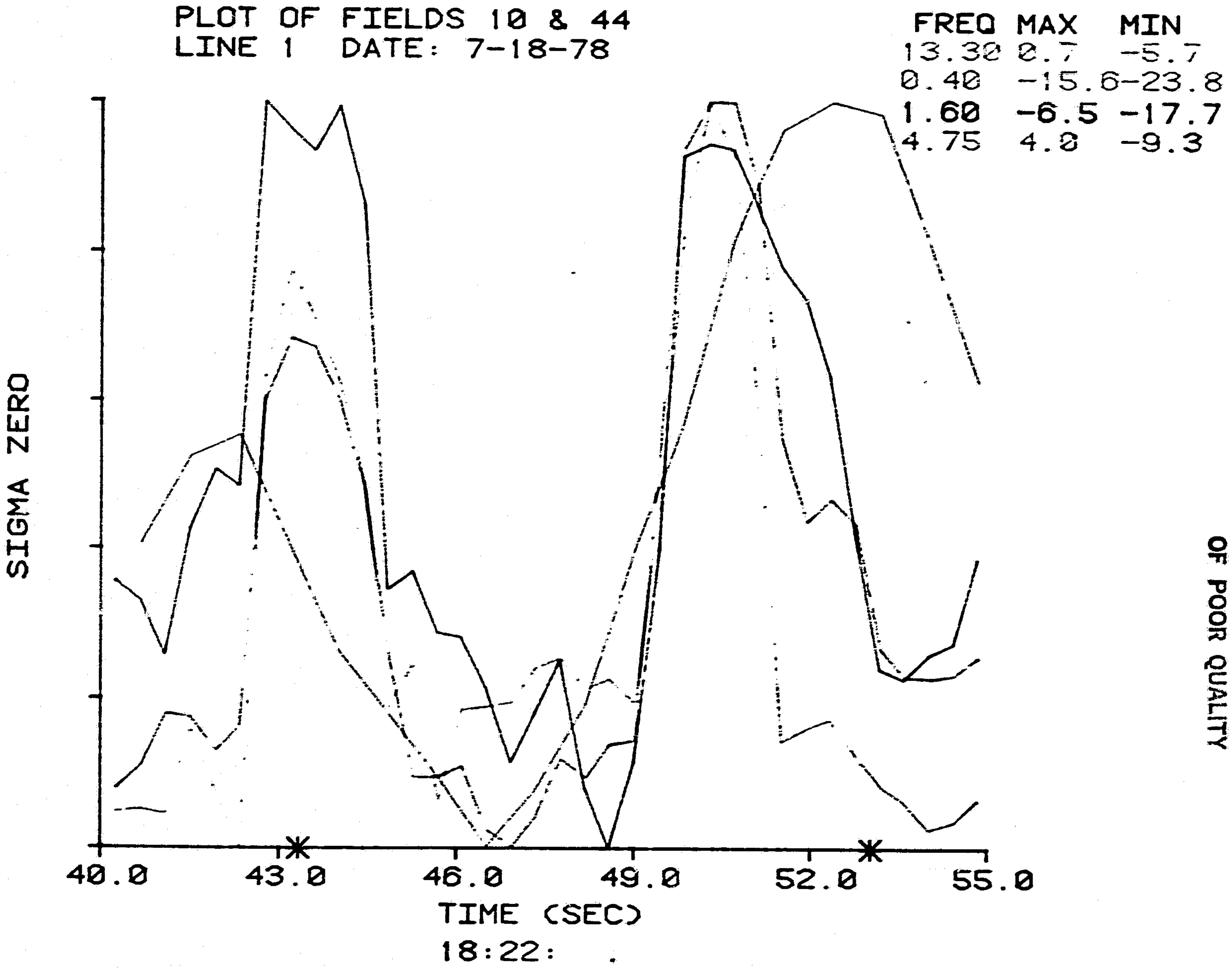
        - VIRTUALLY ALL NATURAL SURFACES EXHIBIT SIGNIFICANT COMPRESSION FOR WAVELENGTHS UP TO 30 CM

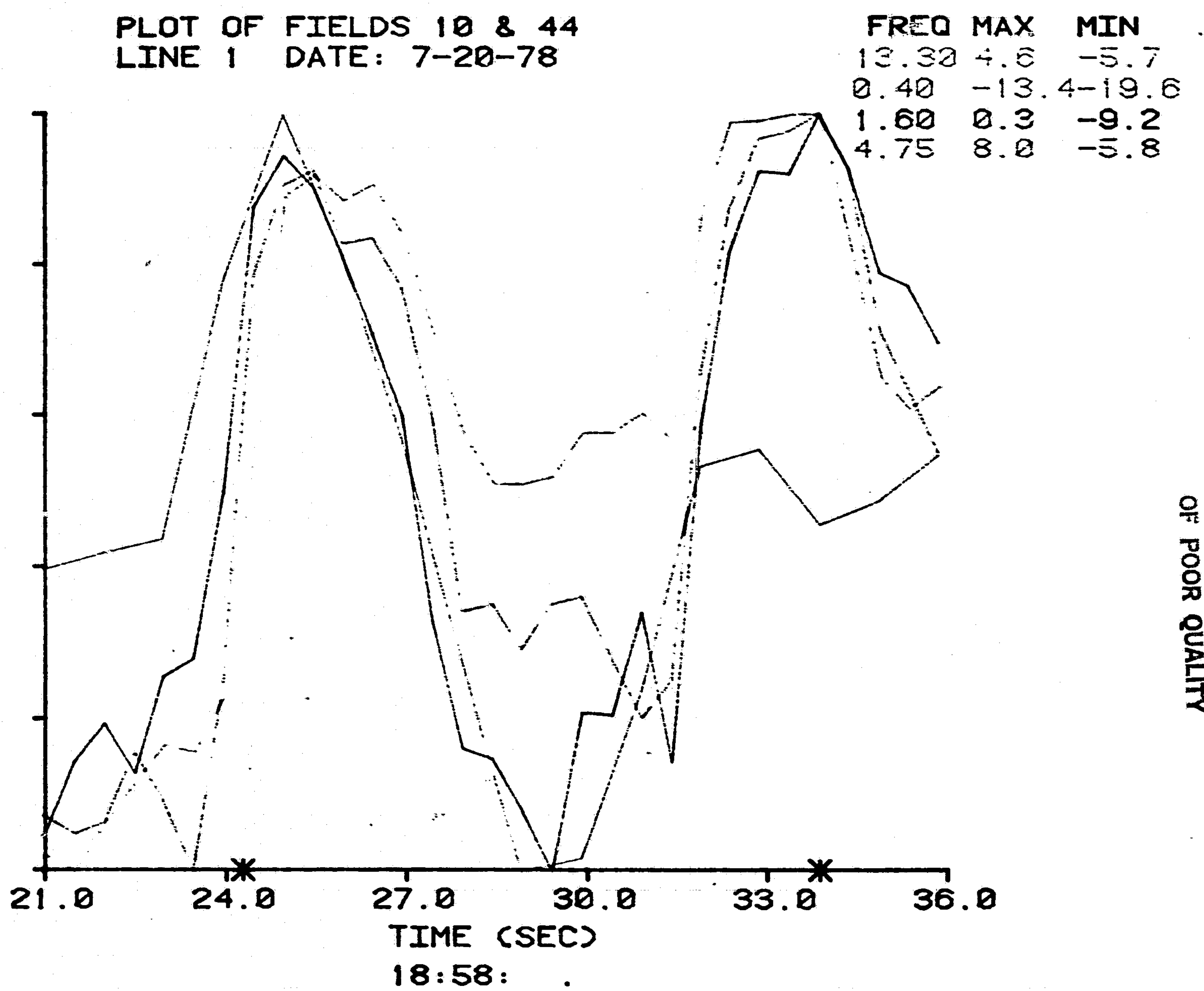
        - COMPRESSION IS ONLY SLIGHTLY DEPENDENT ON FREQUENCY (3-30 CM)

    - LARGE SCALE

        - EFFECT OF ROUGHNESS MASKED BY SOLAR ILLUMINATION EFFECTS AT OFF NADIR ANGLES

- SURFACE TEMPERATURE VARIATIONS CONTRIBUTE SIGNIFICANTLY TO BRIGHTNESS TEMPERATURE SENSITIVITY WHERE EVAPORATION RATE IS ATMOSPHERIC LIMITED


PLOT OF FIELDS 10 & 44
LINE 1 DATE: 7-18-78
FREQ MAX MIN
13.30 0.7 -5.7
0.40 -15.6 -23.8
1.60 -6.5 -17.7
4.75 4.0 -9.3
SIGMA ZERO
40.0
43.0
46.0
49.0
52.0
55.0
TIME (SEC)
18:22:



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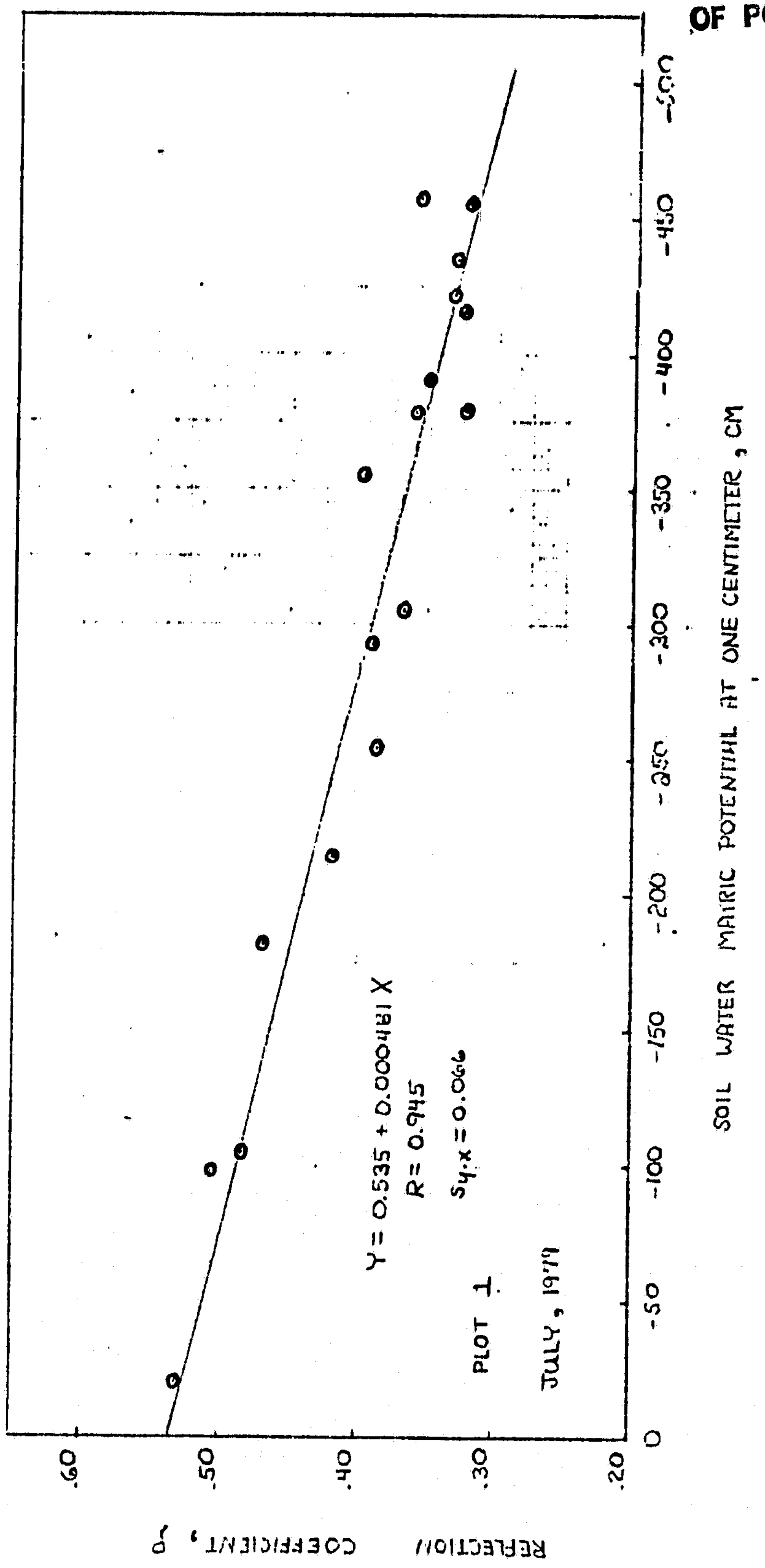
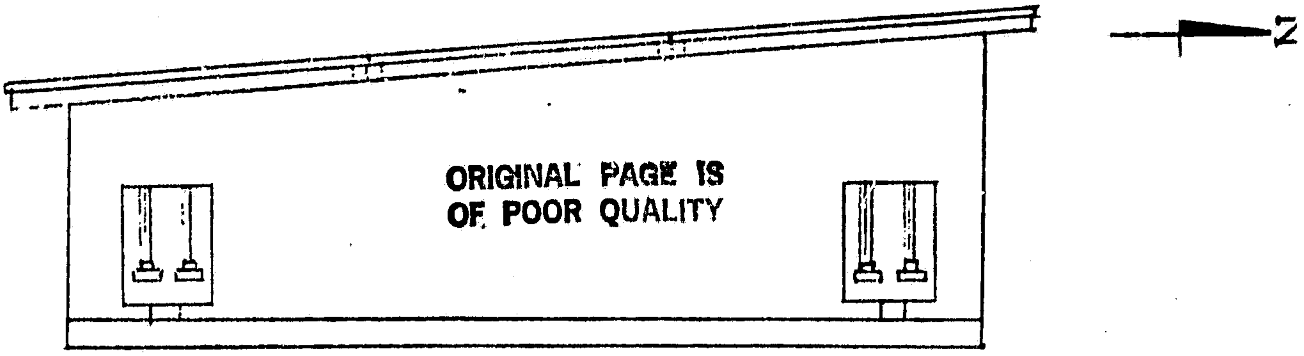
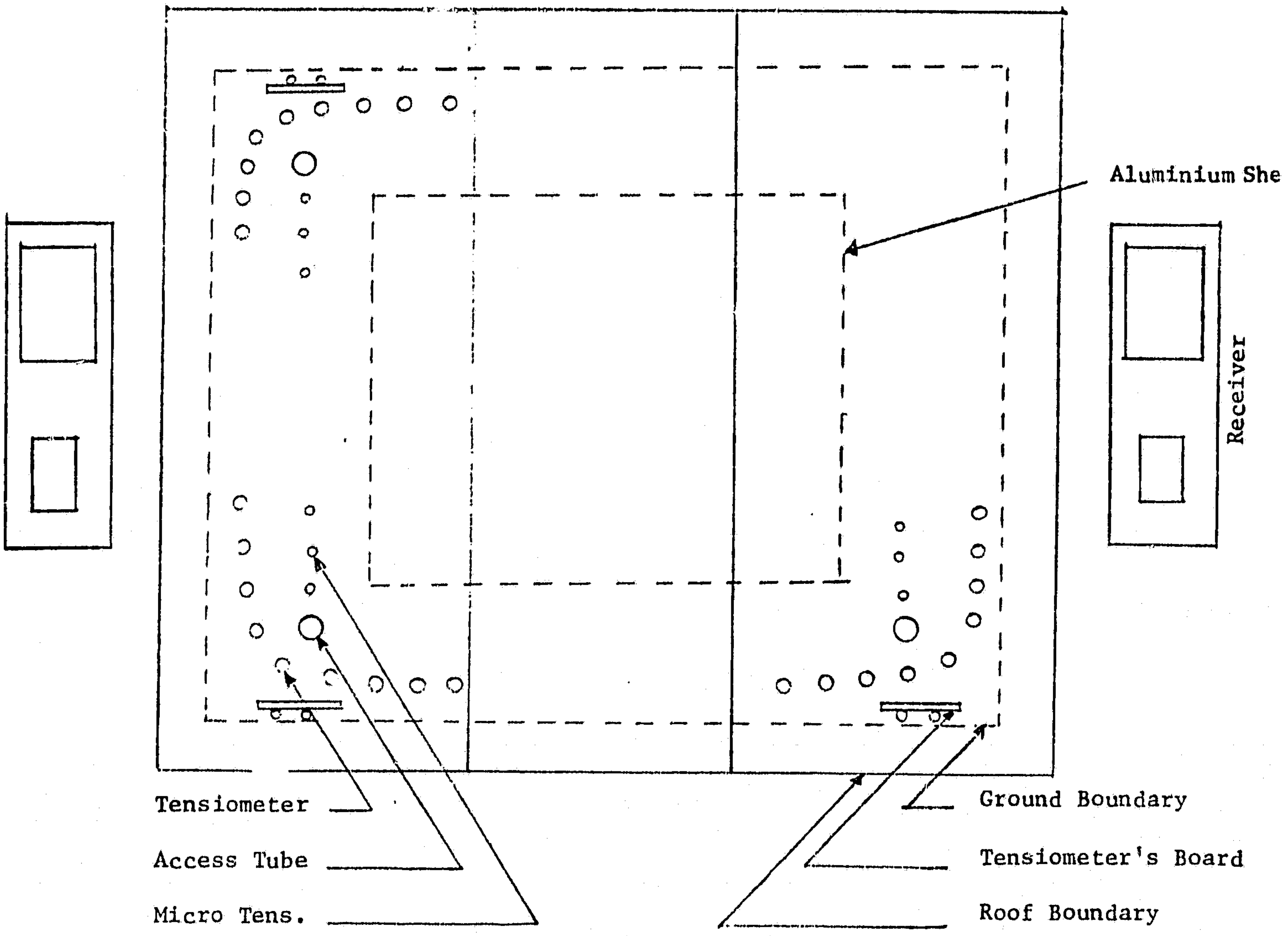




"Side View"



"Top View"

APPENDIX G

PRESENTATION BY GERRY BRADLEY

UNIVERSITY OF KANSAS

SOIL MOISTURE WORKSHOP
Beltsville, Maryland
June 16, 1980

SOIL MOISTURE RESEARCH
University of Kansas

G. A. Bradley
Remote Sensing Laboratory
University of Kansas Center for Research, Inc.
Lawrence, Kansas 66045

This report describes the status of the Soil Moisture Research Program at the University of Kansas and, in particular, the progress of the program following its incorporation into AgRISTARS. The report is divided into the following five sections: (I) background of the research; (II) status of the truck-radar research; (III) truck/aircraft radar comparison; (IV) aircraft data results; and (V) future plans.

I. BACKGROUND

The KU Soil Moisture Research Program began in 1974 when a truck-mounted, wide-frequency-band radar was built to investigate experimentally the relationship of radar backscatter to the agricultural scene parameters of soil moisture, surface roughness, soil texture, and vegetation cover. The radar was designed to measure the backscatter coefficient at frequencies between 1-18 GHz, incidence angles between 0° and 70°, and polarizations of HH, HV, and VV. The objective was to determine if soil moisture could be estimated from a radar remote sensor by using a unique combination of radar parameters having the highest sensitivity to soil moisture and the least sensitivity to other scene parameters.

Radar backscatter theories universally agree that σ^0 is dependent upon the reflection coefficient R and a scene roughness parameter. Newton at Texas A&M University showed (1977) that the reflection coefficient R expressed in dB is linearly related to soil moisture. Therefore, σ^0 in dB should also be linearly related to soil moisture and this has proved to be the case in our experimental measurements. In 1974 and 1975,

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radar experiments were conducted on bare soil to determine the dependence of σ^o on surface roughness. The results of these measurements [Ulaby, et al., 1978] showed that small-scale roughness effects are minimized in the σ^o measurement if the angle of incidence is 10°-20°. These measurements showed also that the correlation between σ^o and soil moisture is maximum for frequencies in the C-band (4-5 GHz) region and for HH polarization. Newton showed also that the reflection coefficient versus soil moisture relationship is dependent upon soil texture. We have used his data together with soil tension versus moisture estimates to show that reflection coefficient and σ^o(dB) are independent of soil texture if a normalizing function keyed to soil tension is used as the soil moisture variable. In 1975 and 1977, our soil moisture experiments included soil tension estimates which showed that the dependence of σ^o on soil texture can be minimized by using a normalizing function for soil moisture.

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II. STATUS OF TRUCK RADAR RESEARCH

Truck-radar soil moisture experiments have been performed during five summers in 1974, 1975, 1977, 1978, and 1979; an experiment currently is in progress in the Lawrence, Kansas area, which will quantify the backscatter dependence on large-scale surface roughness resulting from field-tillage patterns. The following table summarizes these truck-radar experiments.

Summary of KU Truck-Radar Soil Moisture Research Experiments

Year	Location	Purpose	Scene	No. of Data Sets
1974	College Station, TX	Small-Scale Surface Roughness	Bare Soil	40
1975	Eudora, KS	Vegetation Effects	Vegetation	169
	Lawrence, KS	Surface Roughness	Bare Soil	83
1977	Eudora, KS	Vegetation Effects	Vegetation	68
	Eudora, KS	Surface Roughness	Bare Soil	88
1978	Colby, KS	Air/Ground Test	Bare & Veg.	82
1979	Lawrence, KS	Soil Texture	Bare Soil	100
1980	Lawrence, KS	Large-Scale Surface Roughness (Tillage Patterns)	Bare Soil	In Progress

Analysis of the truck-radar data measured in the 1974-77 experiments has resulted in the following major conclusions:

1. The radar σ^o is highly correlated to normalized surface soil moisture. The correlation coefficient is maximum at .883 for radar parameters of 4.625 GHz, HH polarization, and 10° incidence angle.
2. A single algorithm is sufficient statistically to estimate soil moisture for all scenes including those with many types of vegetation cover and for bare soil with varying microroughness. Macroroughness conditions found in tillage patterns may be a special case and currently are being investigated experimentally and theoretically.

3. A simple, non-coherent model fitted with the 1974-77 vegetation and bare data has shown that, at the optimum radar parameters, the mean vegetation canopy attenuation is 1.34 dB and the mean canopy backscatter coefficient is -14.1 dB.
4. The highest correlation occurs for a soil depth of 0-5 cm and for soil moisture expressed as a percentage of field capacity. Field capacity for the 1974-77 data was estimated using Schmugge's one-third bar approximation [3]. Results from the 1979 experiments will show the effects of several soil moisture normalization methods.

The 1979 experimental data currently is being processed and analyzed. Results of this analysis are expected to show the following:

1. The effects of normalization on soil moisture σ^0 estimation algorithms.
2. The dependence of radar σ^0 on soil texture.
3. Spatial and temporal soil moisture variability of fields with five different soil textures measured over a six-month period.

The 1980 experiments currently in progress will quantify the effects of large-scale roughness tillage patterns on the σ^0 soil moisture estimator.

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III. TRUCK/AIRCRAFT RADAR COMPARISON

Using the KU truck-radar and NASA/JSC C130 aircraft, two coordinated experiments have been performed: a small experiment with five fields was conducted in 1976 at Lawrence, Kansas and a major two-month experiment with seven C130 flights was conducted in 1978 at Colby, Kansas. An analysis using the five 1976 fields and 11 of the 19 data sets from 1978 was made to compare the aircraft data with the ground-radar data (the remaining eight data sets are awaiting processing at NASA/Johnson Space Center).

The three aircraft scatterometers show a very high correlation with the KU truck-radar; the correlation coefficients are .918, .877, and .829 for the 1.6 GHz HH, 4.75 GHz HH, and 13.3 GHz VV data, respectively. Because only the truck radar is calibrated to an absolute standard (a wide-band Luneberg lens), correction factors for the aircraft data can be derived by referencing it to the MAS data if there are consistent bias differences between it and the truck data. Four angles for the 4.75 GHz HH aircraft scatterometer and two angles for the 13.3 GHz VV scatterometer were found to have consistent bias differences. With the calibration coefficients applied, the aircraft- and truck-radar regressions are nearly perfect with slopes close to unity and near-zero y-intercepts. This indicates that uncertainties in the aircraft antenna patterns can be compensated for by reference to the truck-radar data. The L-band (1.625 GHz) scatterometer data agreed very closely with the ground-radar data, indicating a very high degree of absolute calibration.

These truck/aircraft radar comparisons are extremely significant because the radars operate very differently with significantly different antenna patterns and, perhaps most important, because very different methods for measuring and processing the data are used. Yet, for 16 entirely different target scenes, the aircraft- and ground-radars measure the same value for σ^0 with a correlation of greater than 0.8. The truck-radar data has been shown to be highly correlated to surface soil moisture. Therefore, the aircraft radar should show also the same high dependence (see next section). Finally, a satellite radar also should be capable of detecting and estimating surface soil moisture.

IV. AIRCRAFT DATA RESULTS

Aircraft data acquired as a result of two flights in 1978 over Colby, Kansas have been analyzed for radar and radiometric soil moisture dependence. To date, 25 fields have been analyzed for the radar σ^0 response and the C-band radiometer temperature response at 0° and 40° incidence angles. There are 10 fields and 19 data sets remaining in these first two flight-data sets. The data from the remaining five flights should be processed as soon as possible by NASA/JSC to permit a timely analysis of the entire data set.

The major conclusions, to date, from the analysis of the aircraft radar data are the following:

1. The highest correlation of σ^0 with soil moisture is for the radar parameters of 4.75 GHz HH polarization, and incidence angles of 10° to 20°. The correlation coefficient for parallel-tilled (referenced to the flight direction) and non-tilled fields is greater than 0.82. This agrees with the truck-radar conclusions.
2. For like-polarization radar data, field-tillage patterns cause bias shifts in the radar response at incidence angles approximately equal to the average slope of the pattern when the direction of flight is perpendicular to the row pattern. Thus, there are three categories of radar response: (1) non-tilled and parallel fields, (2) perpendicular wheat fields, and (3) perpendicular non-wheat fields. Correlations between σ^0 and soil moisture are greater than .75 for data classified in these three categories for the radar at 4.75 GHz HH, 10° to 20°.
3. For cross-polarization radar data, field-tillage patterns are not a factor; this is an important result because a single soil-moisture estimation algorithm could be used regardless of scene characteristics.. Correlation coefficients are greater than .7 for 4.75 GHz HV, 10° to 20°. However, a radar operating in the cross-polarization mode must have a sufficiently low noise-floor to be able to detect σ^0 in the -20 to -30 dB range of values.

4. A comparison of the data sets taken by the KU MAS ground-radar shows good agreement with the trend of the radar data for the several classification-categories at 4.75 GHz HH, 10°, when the calibration factor of 4.2 dB is applied. A comparison of the MAS algorithms for the 1974-77 data shows a slightly different slope than does the aircraft algorithm; it is believed that this is due to the different categories of targets in the two data sets.

The aircraft C-band radiometer data resulting from the first two flights of the 1978 Colby experiment was analyzed for 28 fields. Several important conclusions have been reached, as follows:

1. There is no row-direction dependence in the brightness temperature versus soil moisture relationship. There is polarization dependence at 40° incidence angle but not at 0°.
2. Radiometric temperature is highly correlated to soil moisture (greater than .85) for bare soil or wheat stubble at both 0° and 40°.
3. The radiometric correlation with soil moisture is lower and the sensitivity is extremely low for cornfields at 0° and 40°. The capability of the radiometer to sense soil moisture is severely reduced by the canopy cover.

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V. THE FUTURE

Our plans for the near future include the following:

1. Completion of the data analysis for the 1978 and 1979 experiments.
2. To conduct a quantitative large-scale roughness tillage-pattern experiment in the summer of 1980.
3. To plan and execute a series of RB57 C-band SLAR experiments over a Lawrence, Kansas test-site in 1981.
4. To perform laboratory research to investigate the dielectric coefficient of soil and water mixtures.
5. To conduct experiments with our new dual-frequency (2.695/4.995 GHz) radiometer in combination with the MAS 1-8 GHz.
6. To continue simulation studies of soil moisture imagery.

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[1] Newton, R. W., "Microwave Remote Sensing and its Application to Soil Moisture Detection," Technical Report RSC-81, Texas A&M University Remote Sensing Center, College Station, Texas, January 1977.

[2] Ulaby, F. T., P. O. Batlivala and M. C. Dobson, "Microwave Backscatter Dependence on Surface Roughness, Soil Moisture, and Soil Texture: Part I--Bare Soil," IEEE Transactions on Geoscience Electronics, Vol. GE-16, No. 4, October 1978.

[3] Schmugge, T., B. J. Blanchard, W. J. Burke, J. F. Paris and J. R. Wang, "Results of Soil Moisture Flights During April, 1974," NASA Technical Note D-8199, 1976.

Published Papers*

1. Ulaby, F. T., G. A. Bradley and M. C. Dobson, "Microwave Backscatter Dependence on Surface Roughness, Soil Moisture, and Soil Texture: Part II--Vegetation-Covered Soil," IEEE Transactions on Geoscience Electronics, Vol. GE-17, No. 2, April 1979.

2. Ulaby, Fawwaz T. and J. E. Bare, "Look Direction Modulation Function of the Radar Backscattering Coefficient of Agricultural Fields," Photogrammetric Engineering and Remote Sensing, Vol. 45, November 1979.

3. Ulaby, Fawwaz T., "Active Microwave Sensing of Soil Moisture: Synopsis and Prognosis," Institute National Agronomique, Paris, France, April 4-6, 1979.

4. Ulaby, F.T., G. Bradley and C. Dobson, "Potential Application of Satellite Radar to Monitor Soil Moisture," AWRA Fifth Annual William T. Pecora Memorial Symposium, Sioux Falls, South Dakota, June 11-15, 1979.

5. Ulaby, Fawwaz T., M. C. Dobson and G. A. Bradley, "Radar Reflectivity of Bare and Vegetation-Covered Soil," Proceedings of the 23rd Annual Conference of the Committee on Space Research (COSPAR), Budapest, Hungary, June 2-14, 1980.

6. Dobson, M. C. and F. T. Ulaby, "Microwave Backscatter Dependence on Surface Roughness, Soil Moisture, and Soil Texture: Part III--Soil Tension," accepted for publication in the IEEE Transactions on Geoscience and Remote Sensing.

*Papers published during the period 1979-1980.

SOIL MOISTURE RESEARCH

UNIVERSITY OF KANSAS

G. A. Bradley

Soil Moisture Workshop

Beltsville, Maryland

June 16, 1980

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RADAR REMOTE SENSING OF SOIL MOISTURE
UNIVERSITY OF KANSAS

1. Background

2. Status of truck radar research

3. Truck/aircraft radar comparison

4. Aircraft data results

5. Future plans

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BACKGROUND

Radar Target Parameters:

- Soil Moisture
- Surface Roughness
- Soil Texture
- Vegetation Cover

Radar Parameters

- Frequency
- Angle
- Polarization

$$\sigma^o(dB) = R(dB)\, f\,(\text{roughness})$$

$$R(dB) = A\ M_N + B$$

$$\sigma^o(dB) = A'\ M_n + B'$$

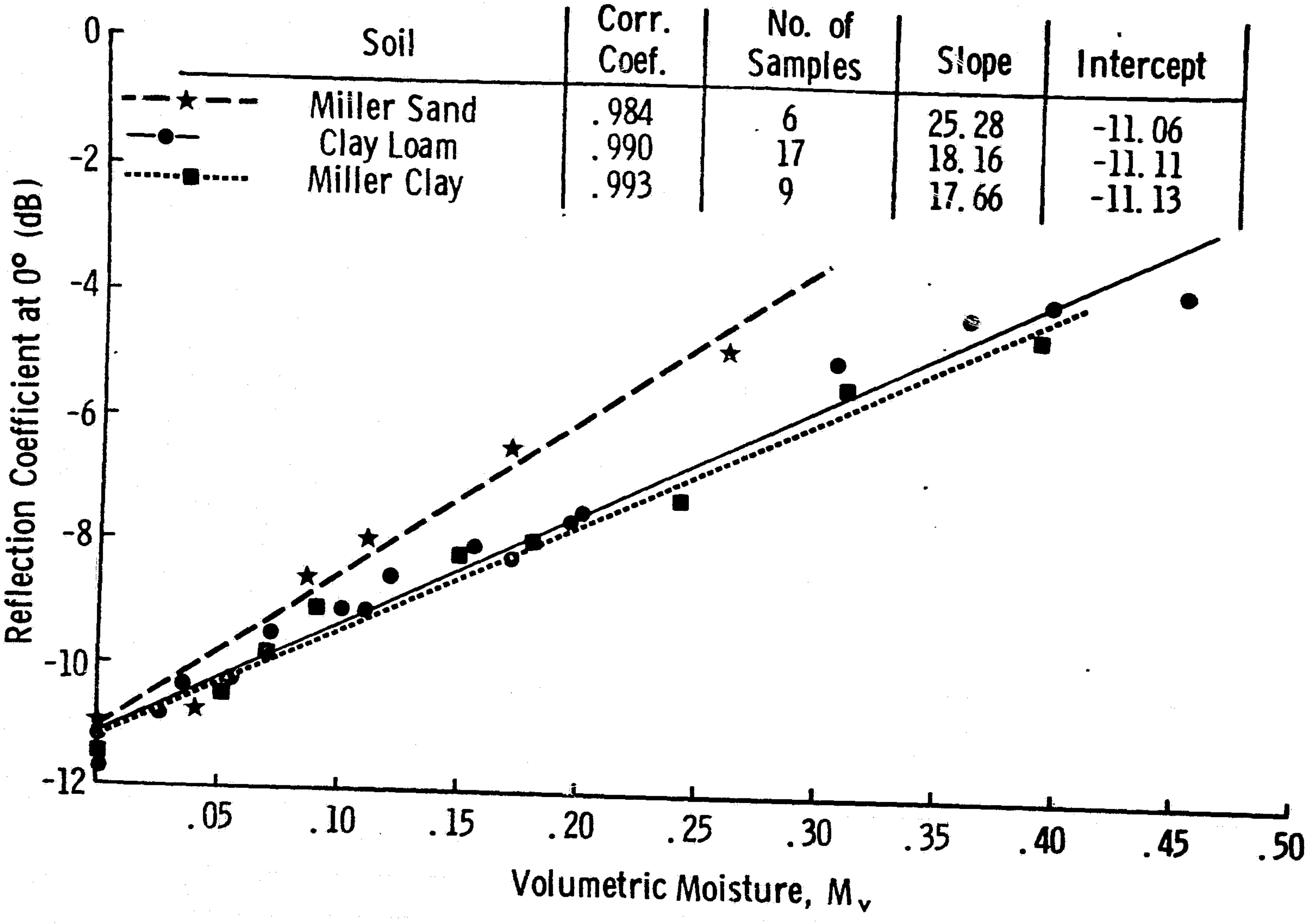

Figure 11 Reflection Coefficient (dB) at 1.4 GHz, 0° as a Function of Volumetric Soil Moisture for Sand, Clay Loam and Clay. (Data from Newton, 1977).

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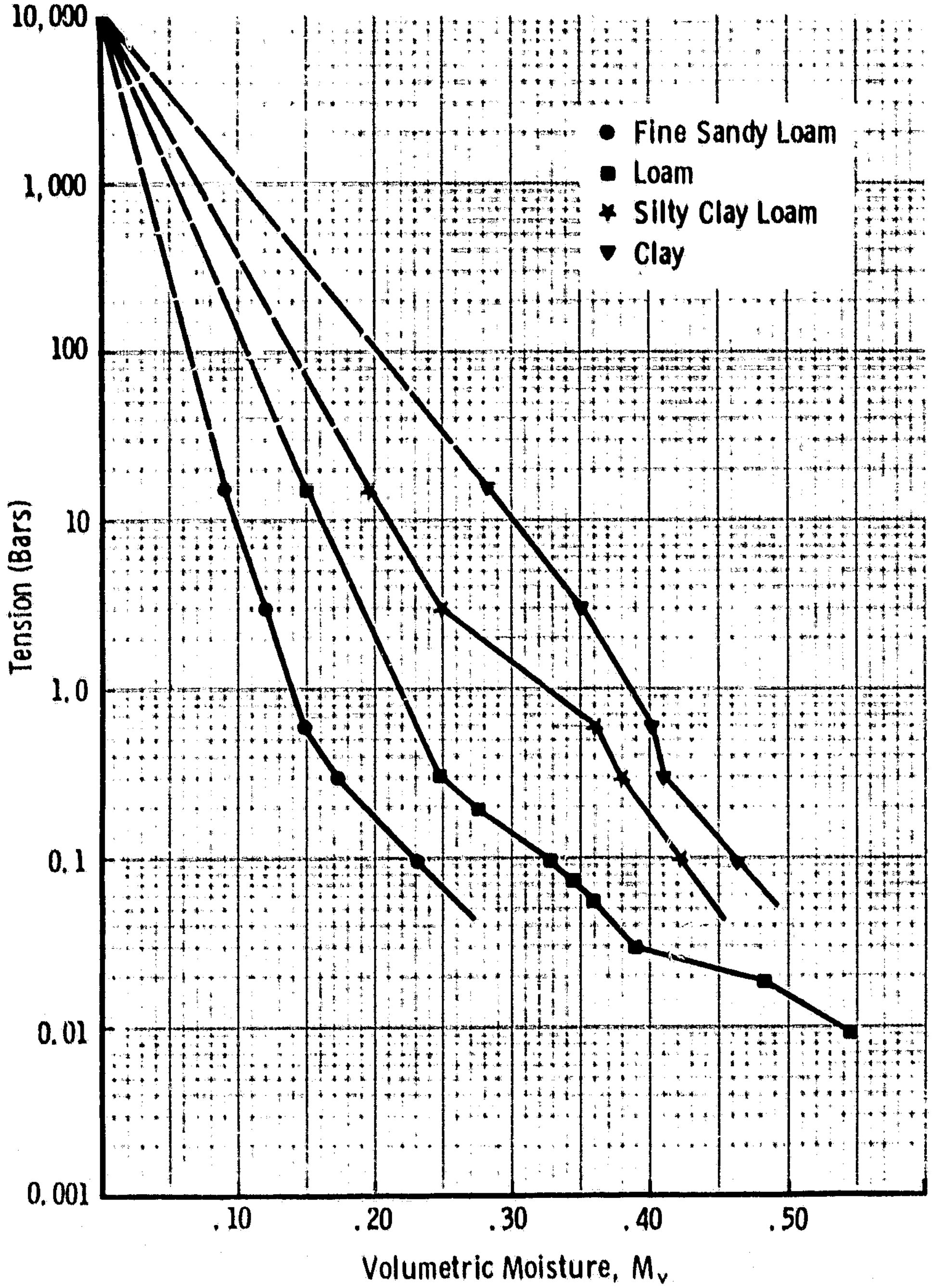
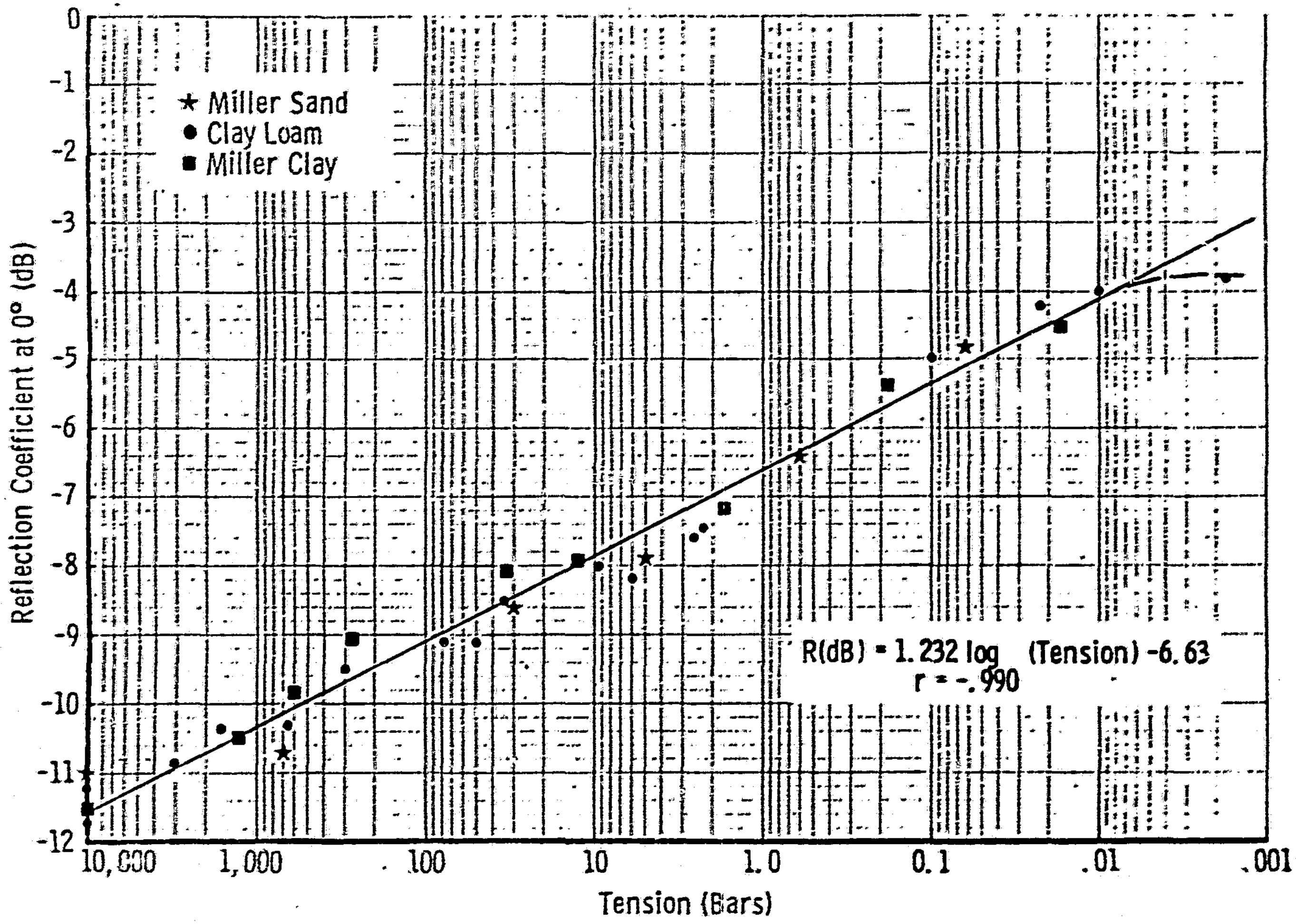
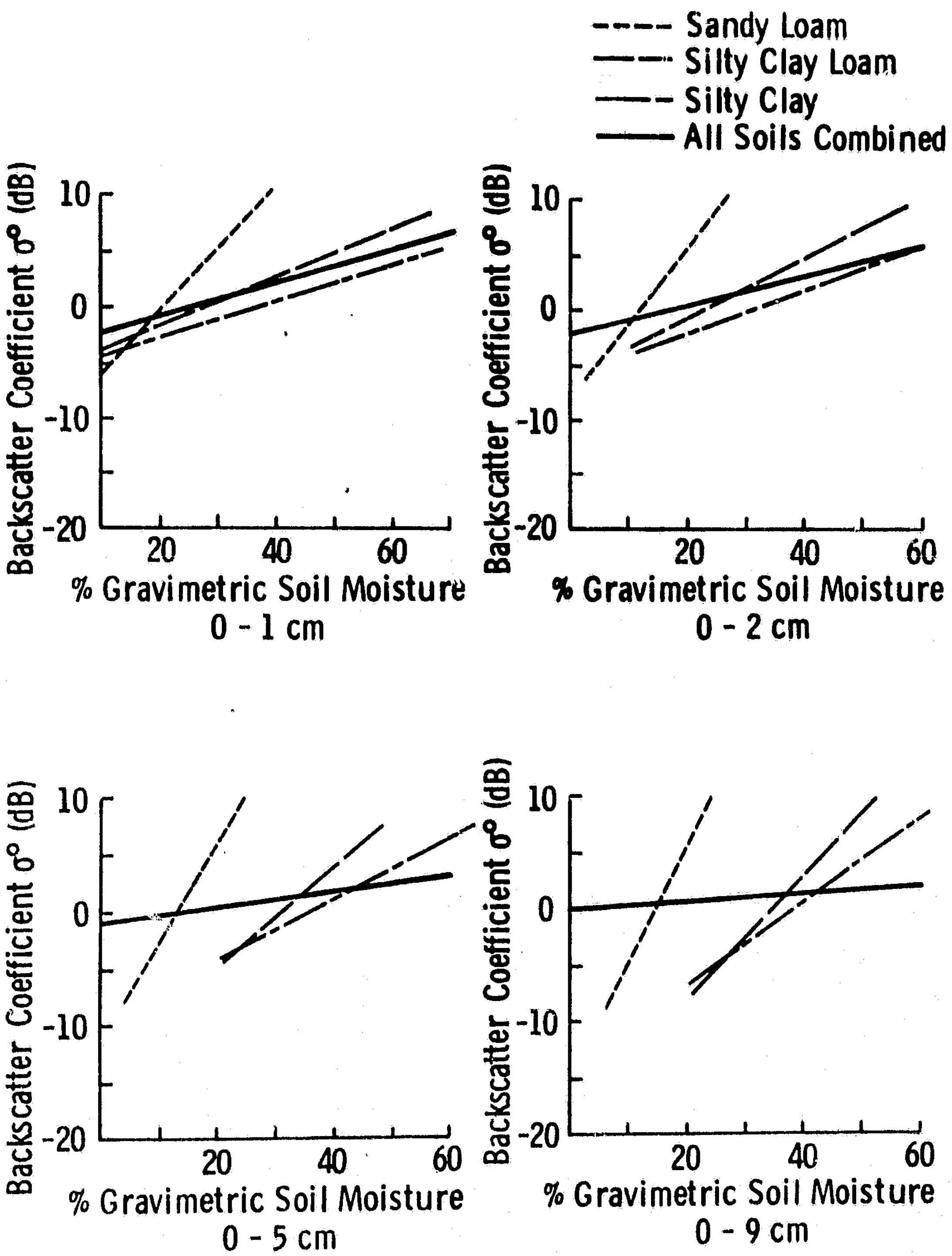


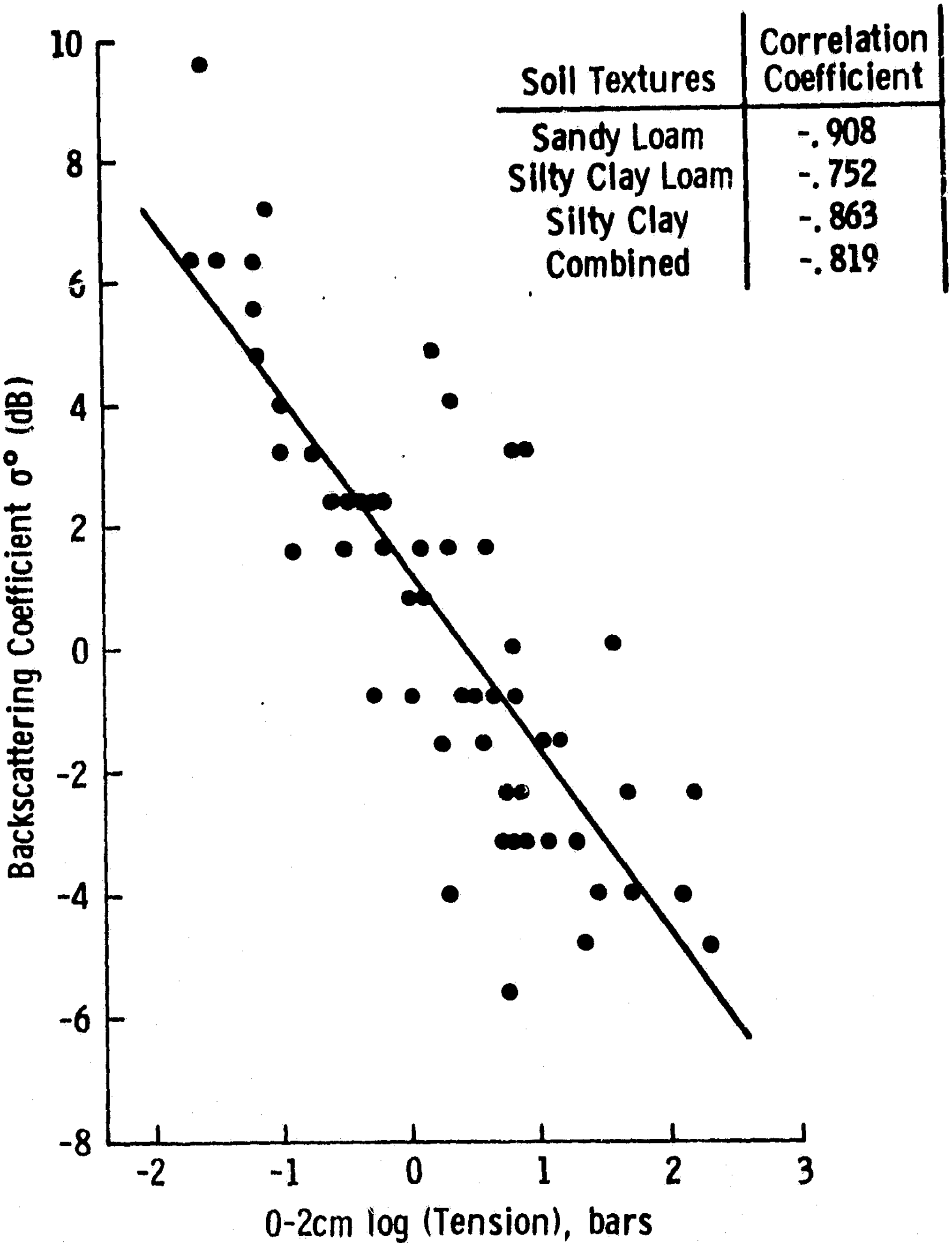
Figure 2.26 Soil Tension as a Function of Volumetric Moisture Content for Various Soil Textures. Data from Holtan, et al. (1968) and Carlisle, et al. (1978)

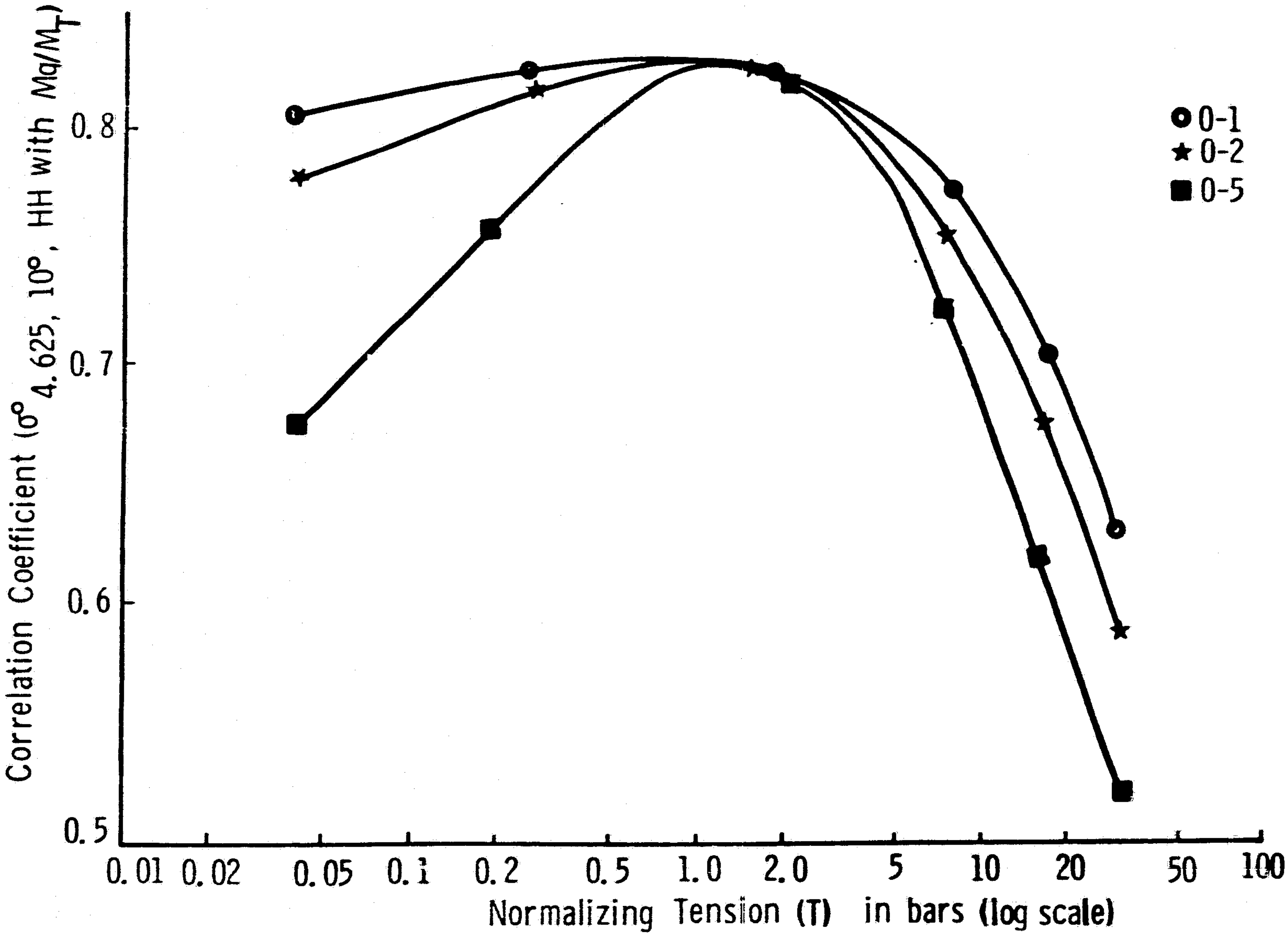
FIGURE 2.29 REFLECTION COEFFICIENT (dB) OF SAND, CLAY LOAM AND CLAY AS A FUNCTION OF SOIL TENSION AT 1.4 GHZ, 0°. (Data from Newton, 1977).




Sandy Loam
Silty Clay Loam
Silty Clay
All Soils Combined
Backscatter Coefficient σ° (dB)
10
0
-10
-20
20
40
60
% Gravimetric Soil Moisture
0 - 1 cm
0 - 2 cm
0 - 5 cm
0 - 9 cm

$\sigma^\circ = -2.849 \log T \text{ (Tension)} + 1.244$





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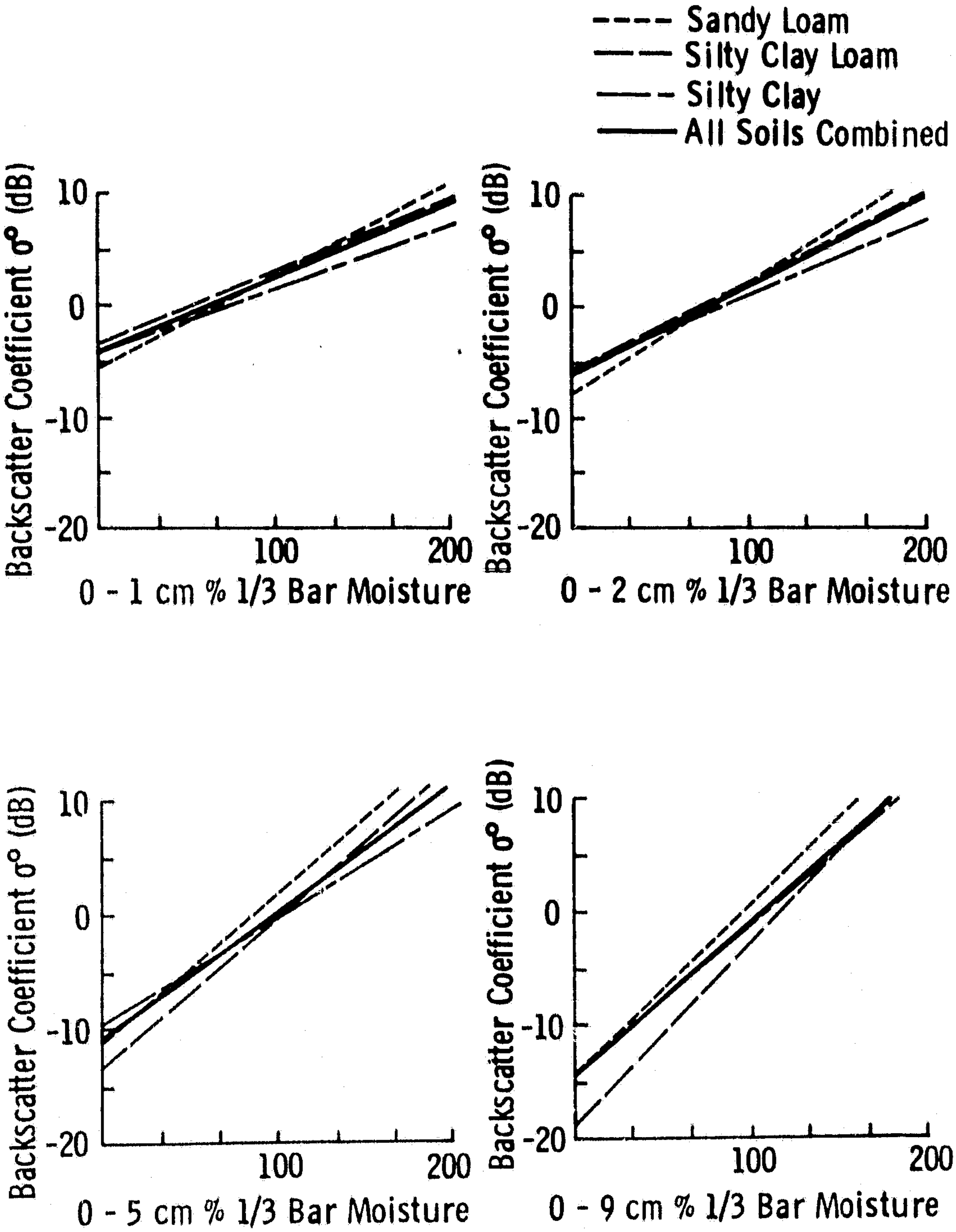
Sandy Loam
Silty Clay Loam
Silty Clay
All Soils Combined
Backscatter Coefficient σ° (dB)
10
0
-10
-20
100
200
0 - 1 cm % 1/3 Bar Moisture
0 - 2 cm % 1/3 Bar Moisture
0 - 5 cm % 1/3 Bar Moisture
0 - 9 cm % 1/3 Bar Moisture

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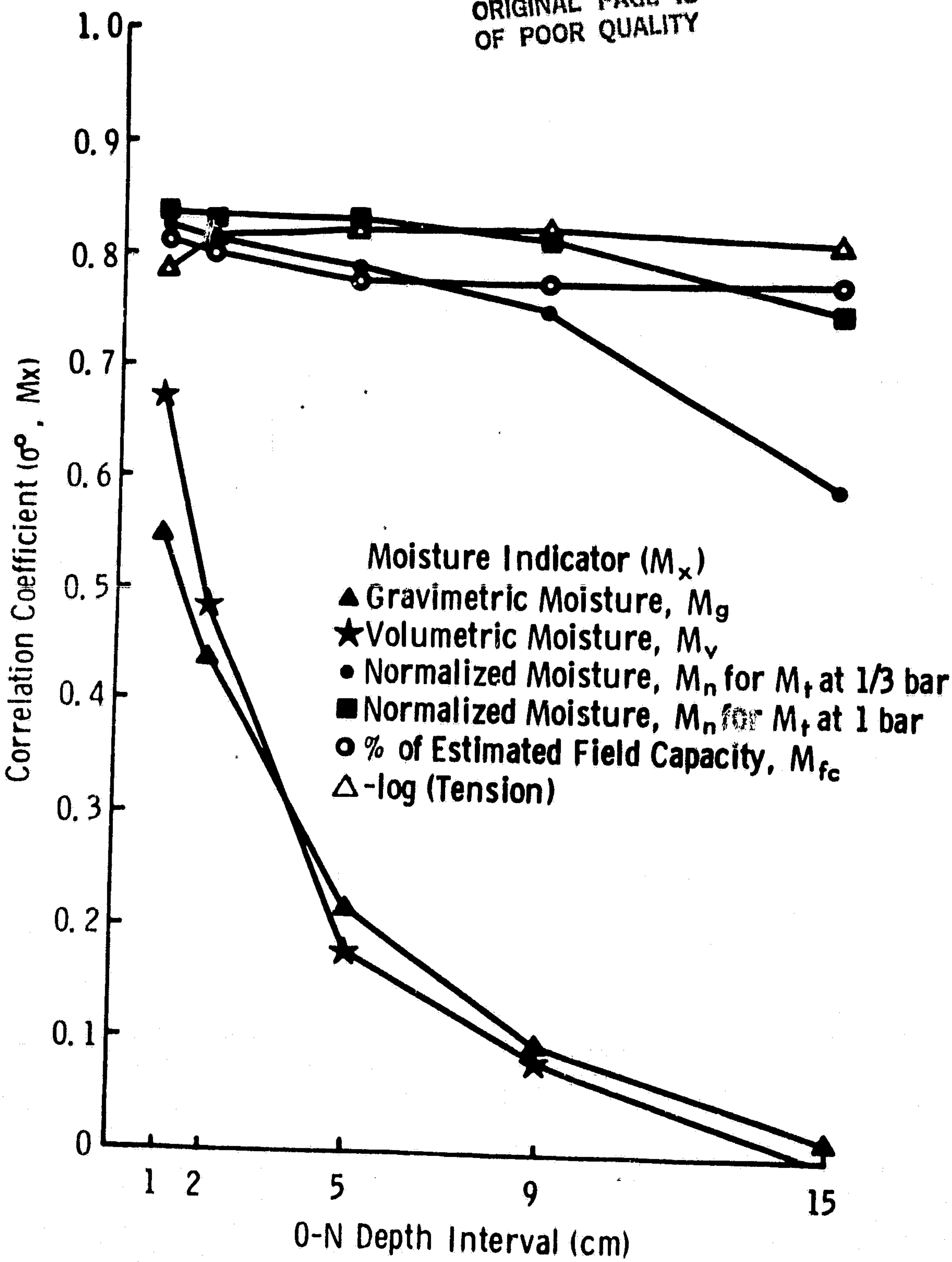

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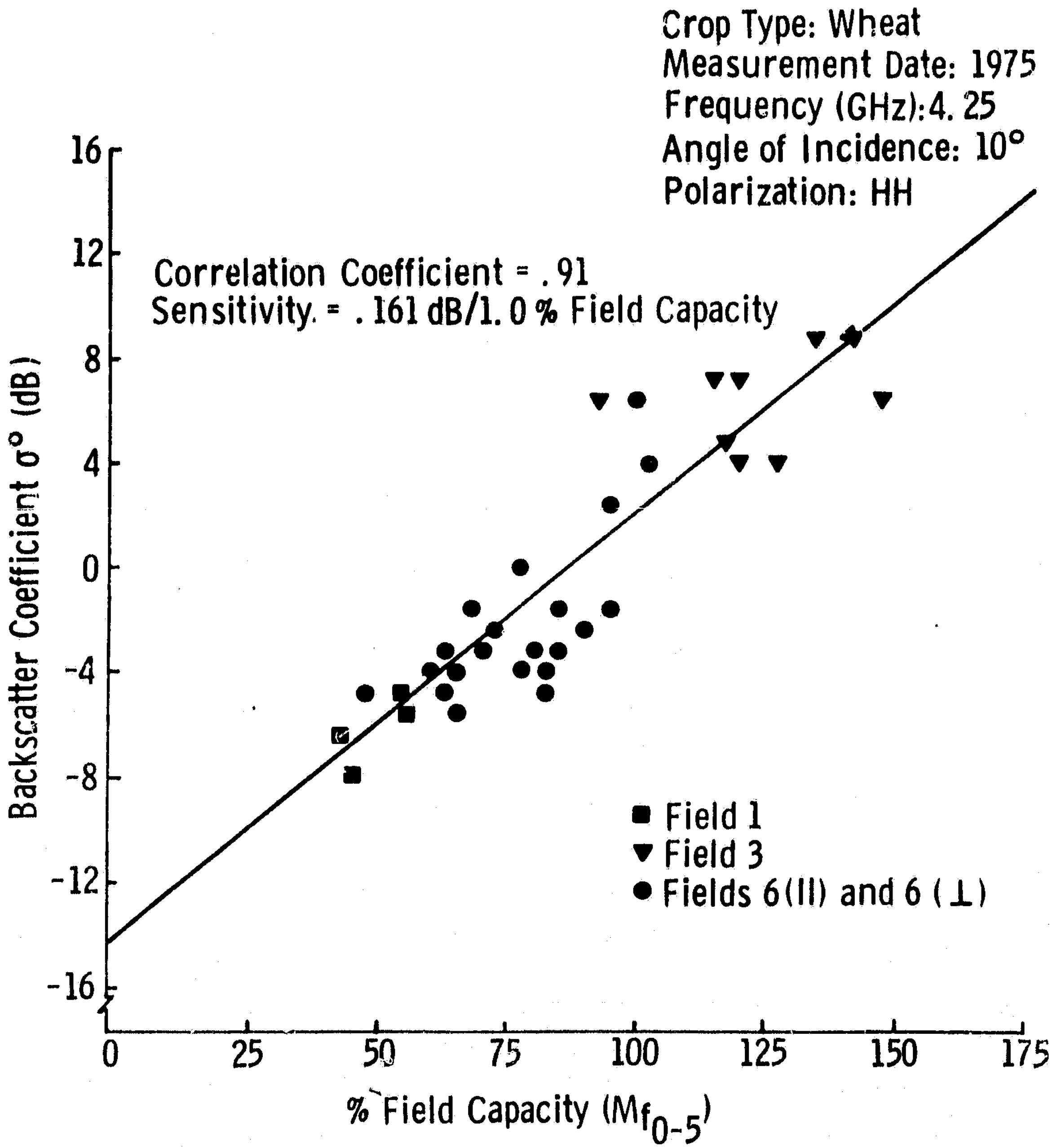

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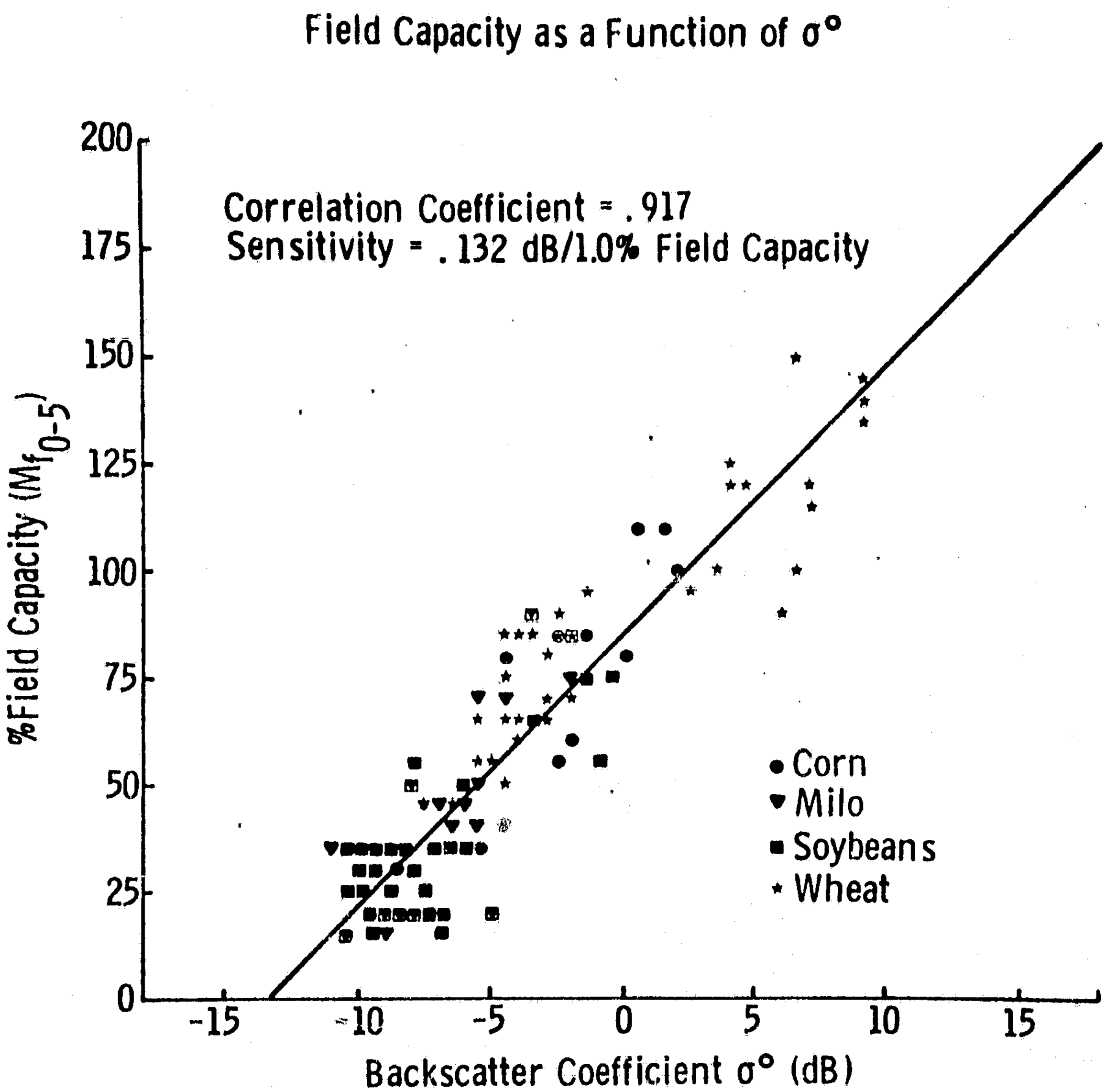
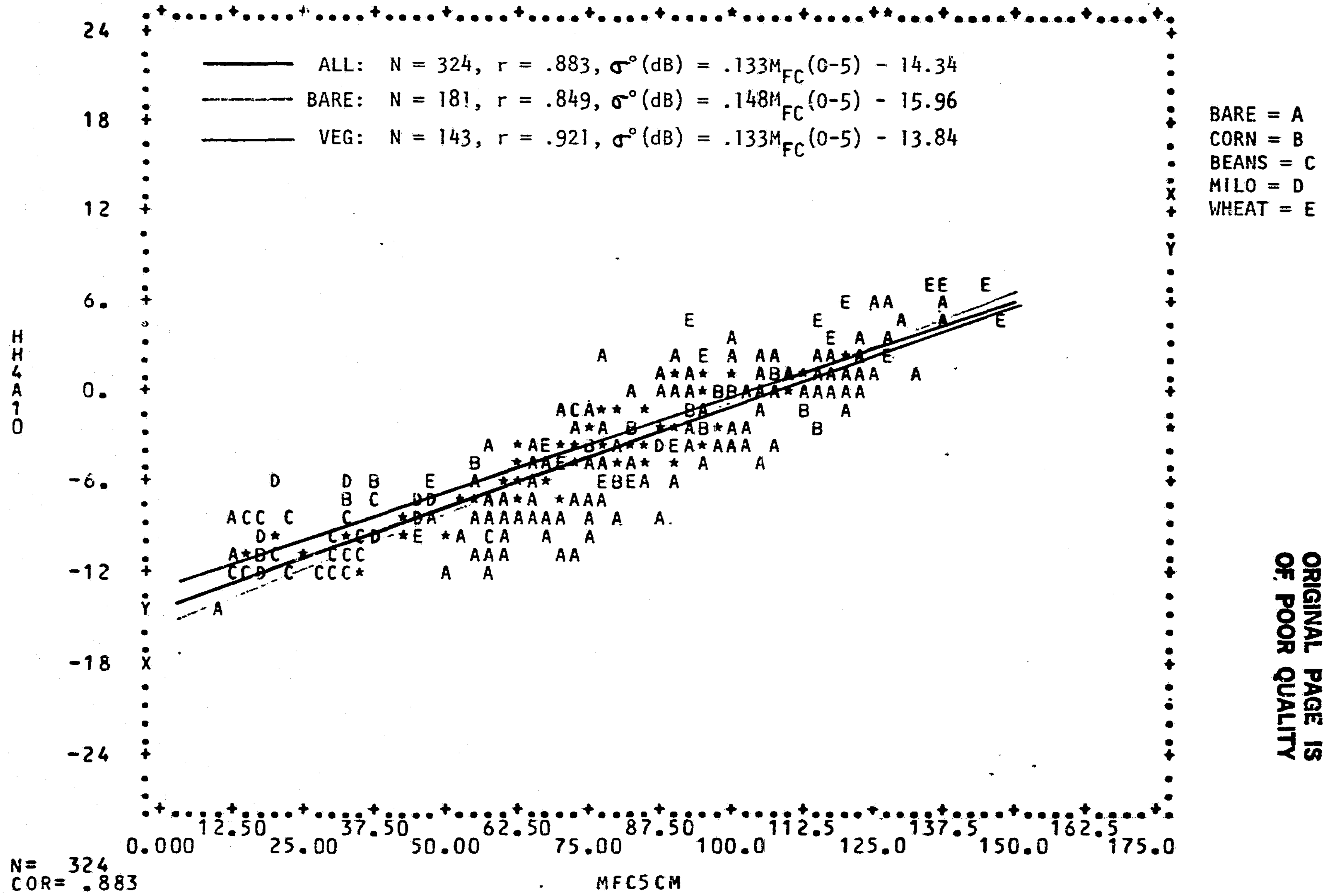


Figure 10. Percent Field Capacity in the 0-5 cm Soil Layer as a Function of Backscatter Coefficient at 4.25 GHz, HH, 10° for Corn, Milo, Soybean and Wheat Data Sets Combined. (Adopted from Ulaby, et al., 1979b)



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MAS Radar Soil Moisture Estimation Algorithm   1974-1977 Experiments   4.625 GHz HH 10°

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Bare: $$\sigma_b^o \left(\frac{m^2}{m^2}\right) = A\ e^{B\ M_n}$$

$$\sigma_b^o\ (dB) = 10 \log A + 4.34\ B\ M_n$$

Vegetation:

$$\sigma_{veg}^o \left(\frac{m^2}{m^2}\right) = \sigma_{canopy}^o + \tau\, \sigma_b^o$$

Fit with MAS 1974-1977 data:

$$\sigma_{canopy}^o = 3.89 \times 10^{-2}\ \frac{m^2}{m^2}$$

$$= -14.1\ dB$$

$$\tau = .735$$

Canopy transmission (2-way) = 10 log .735

= -1.34 dB

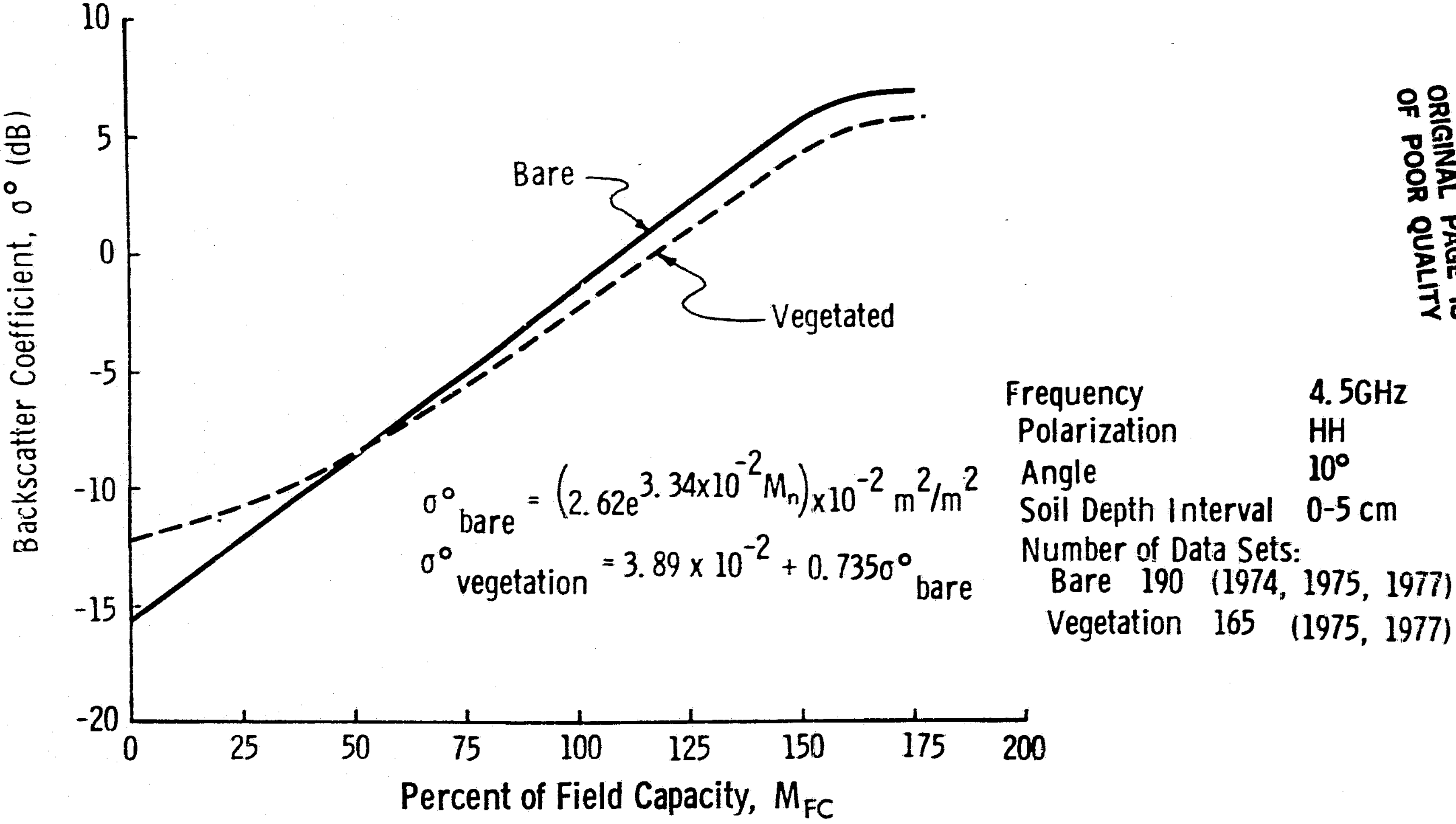

Figure 11. Empirical Model of Radar Response to 0 – 5 cm Normalized Soil Moisture of Bare and Vegetated Fields

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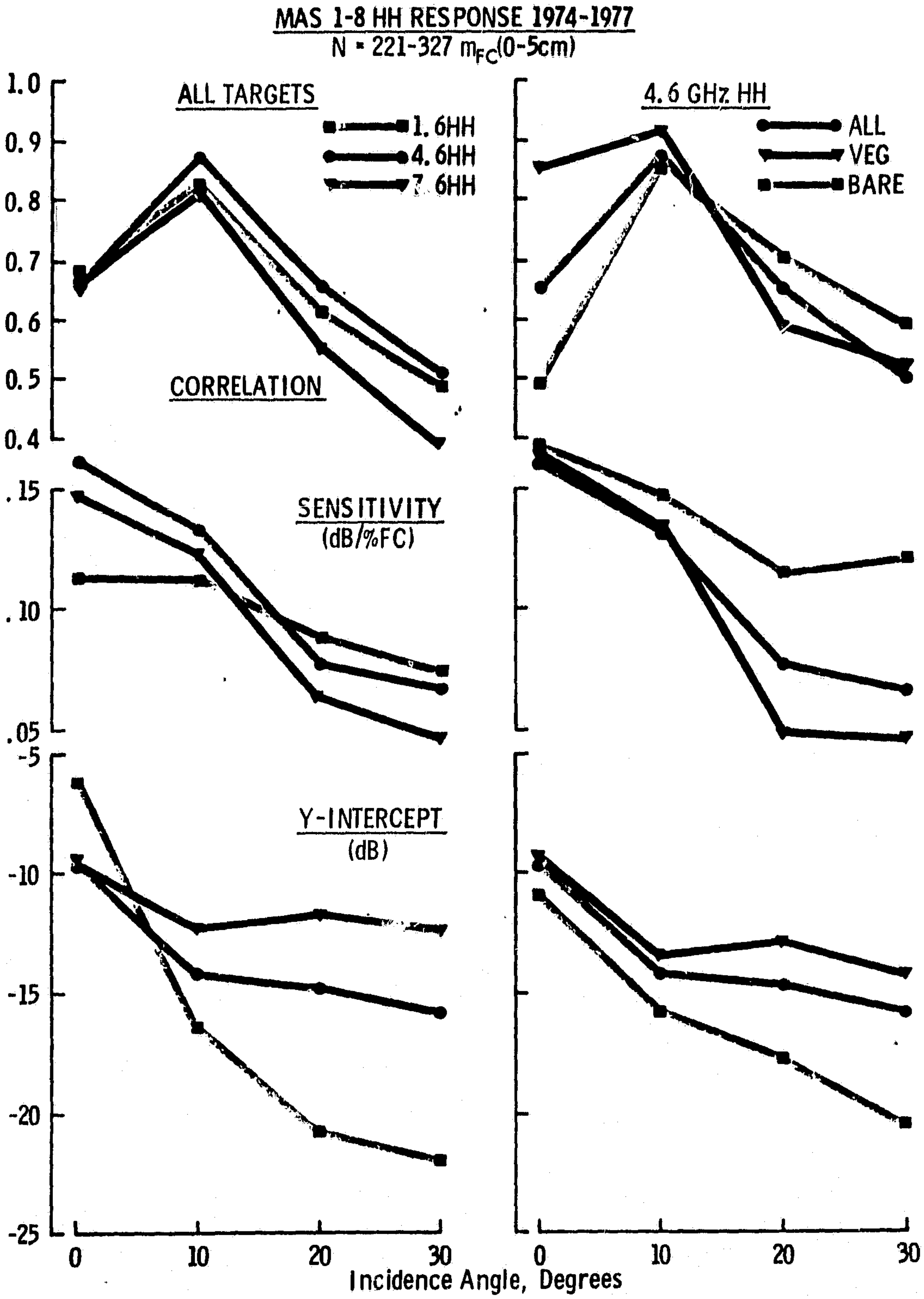


1979 SOIL MOISTURE EXPERIMENT

Purposes:

1. σ^o Soil Moisture Indicator
2. Soil Texture Dependence
3. Spatial & Temporal Variability
4. Tension Measurements

Summary:

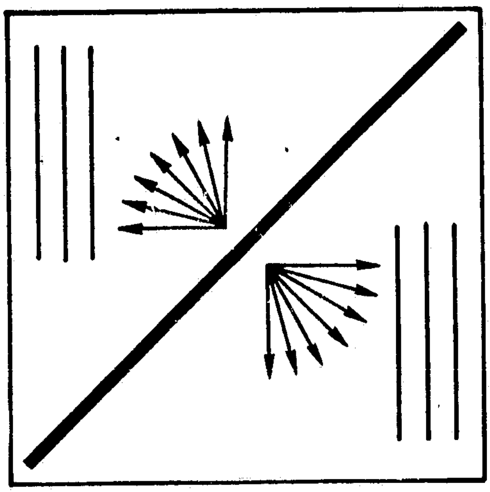
1. 100 Radar 1 - 8 GHz Data Sets
2. Five Fields: Sand-to-Clay
3. Bare Smooth Soil
4. Daily Tension & Resistance Probe Measurements

Status:

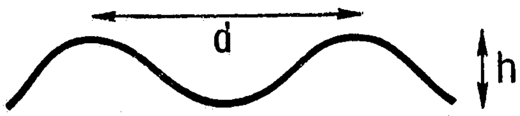
1. Radar data being processed
2. 70 data sets taken by hand being digitized
3. Soils lab data & ground truth data being processed

1980 SOIL MOISTURE EXPERIMENT

Purpose: σ^o Row Direction Dependence Measurement



Experiment: f: 1.6, 2.5, 4.8, 7.6 GHz
P: HH, HV, VV
θ: 0 - 50°
α: 0°, 10°, 22.5°, 45°, 67.5°, 80°, 90°
N: 30 Independent Samples



Furrows: h = 50 - 116 cm
d = 3 - 30 cm

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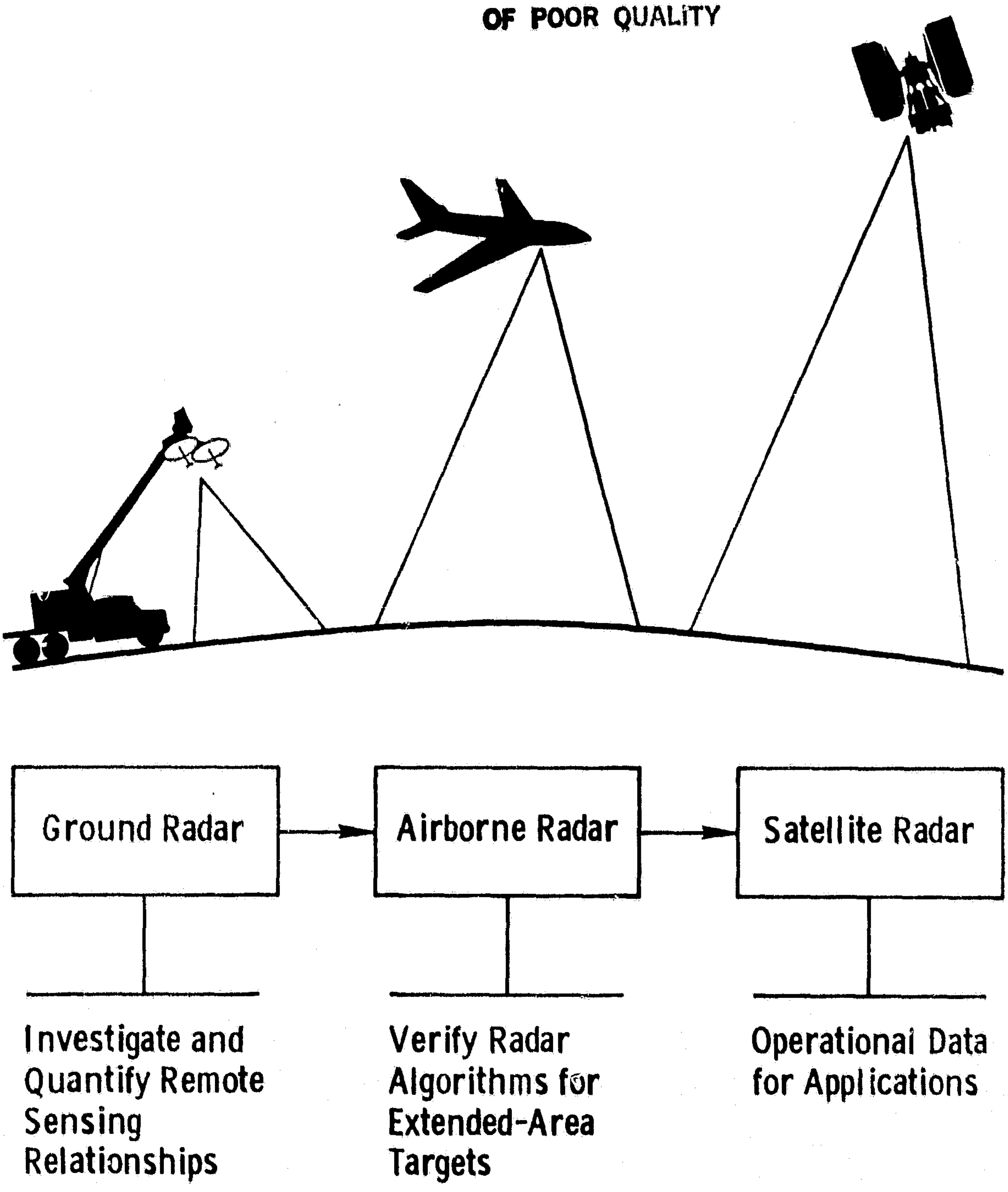

Figure 1. Ground and Airborne Radars can be used to Develop Satellite Remote Sensing Radars.

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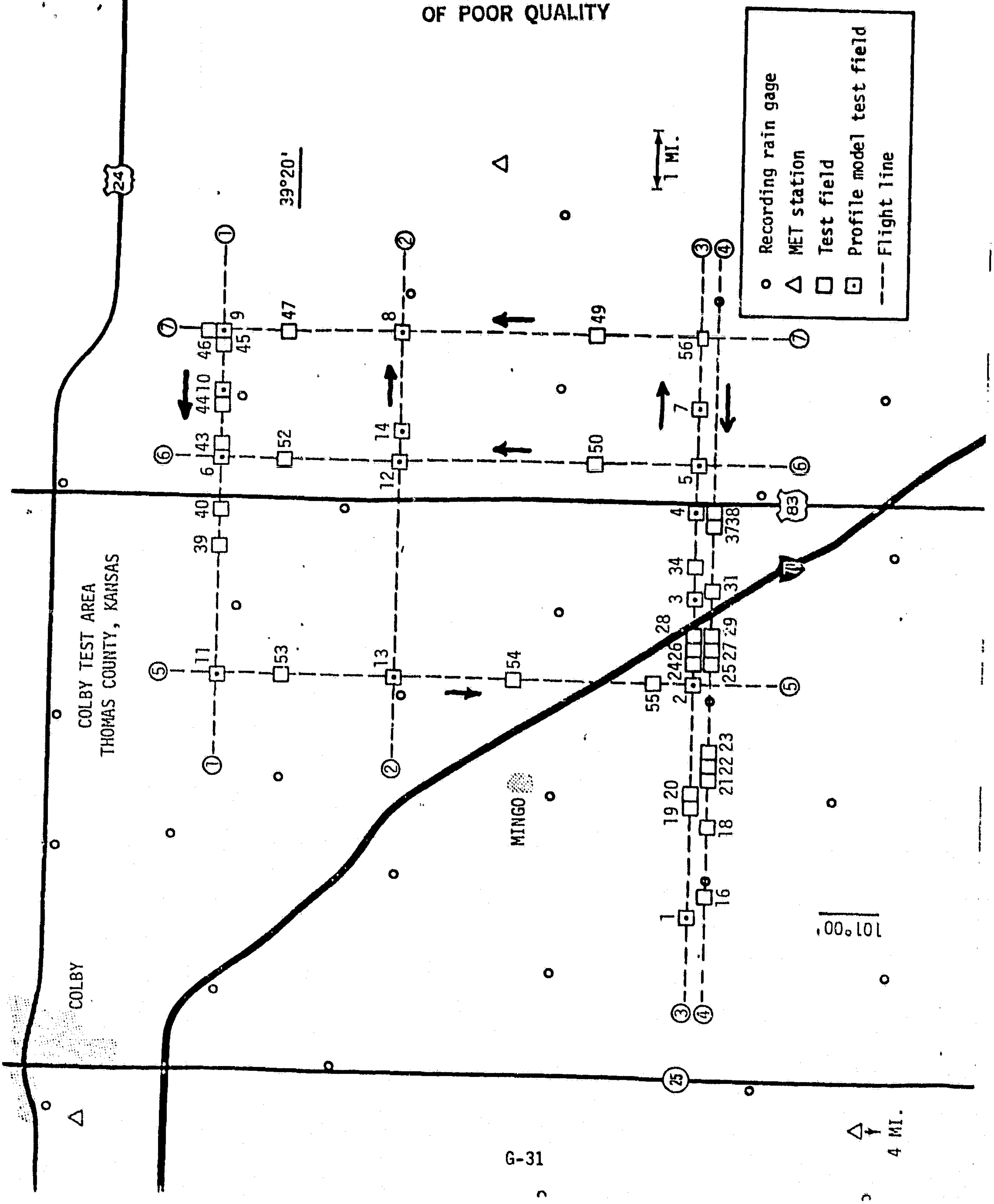

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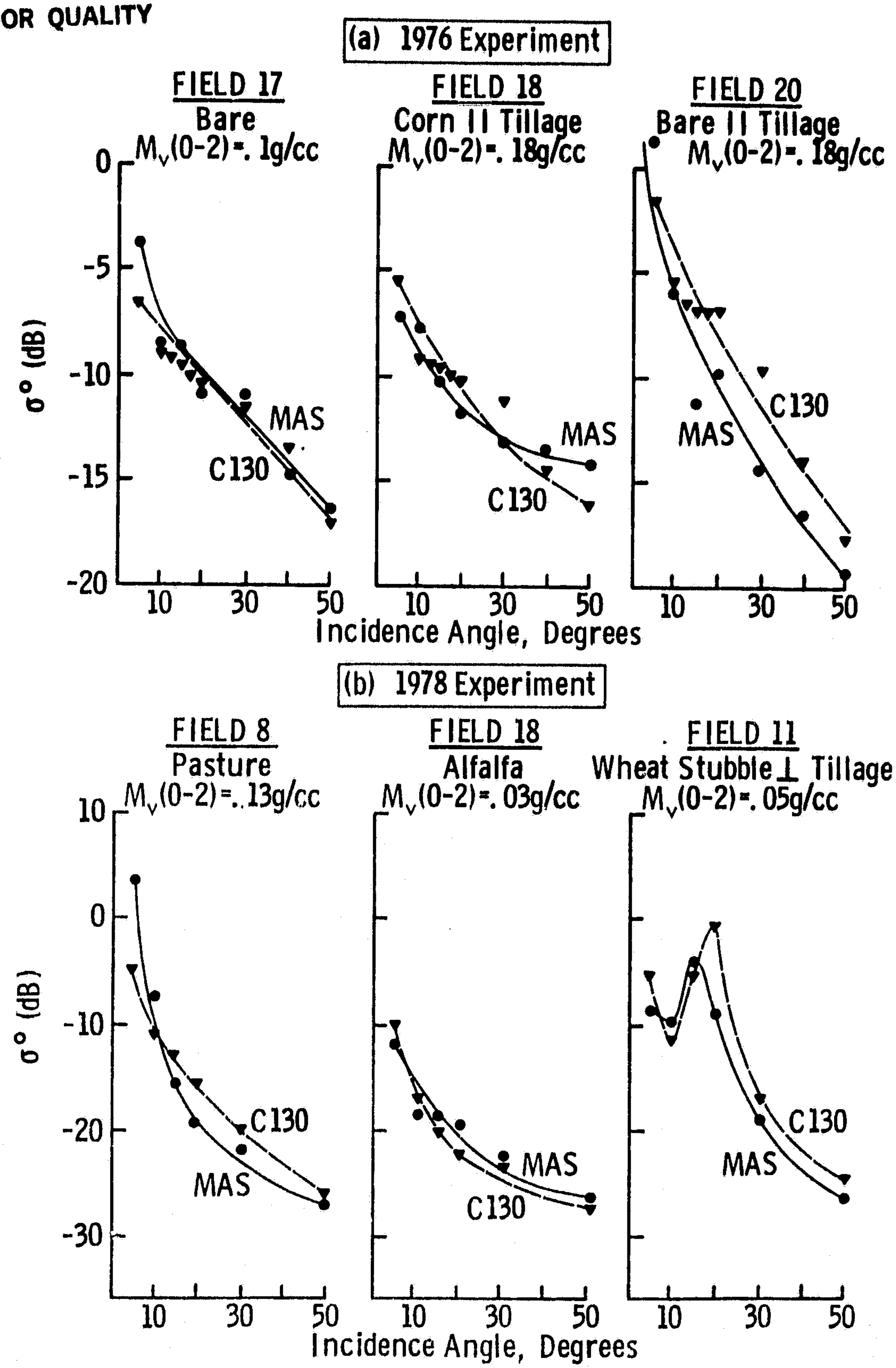


Figure 2. Comparison of 1.6GHz HH MAS and Aircraft Scatterometer Data for Various Terrain Types.

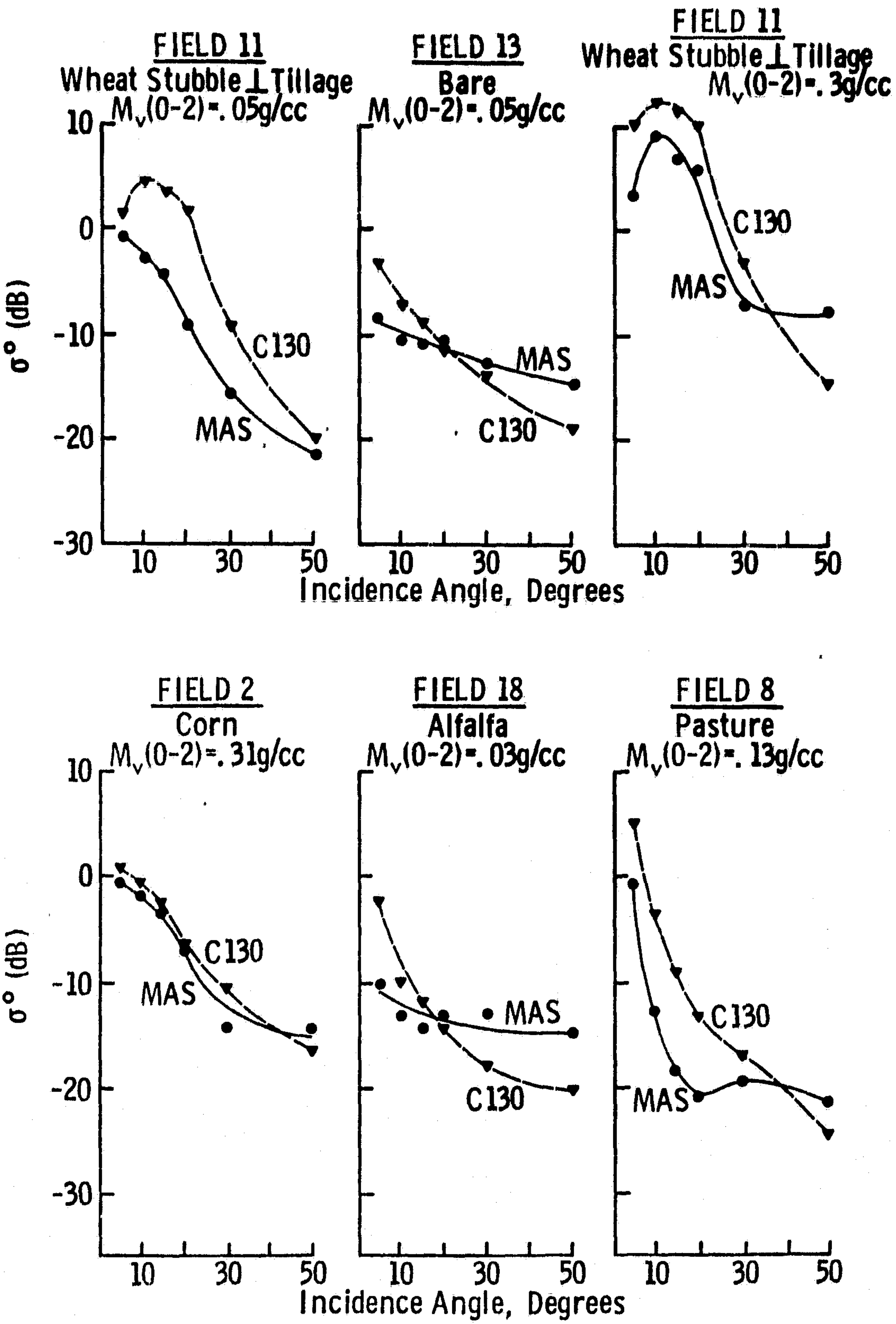


Figure 3. Comparison of 1978 4.75GHz HH MAS and Aircraft Scatterometer Data for Various Terrain Types.

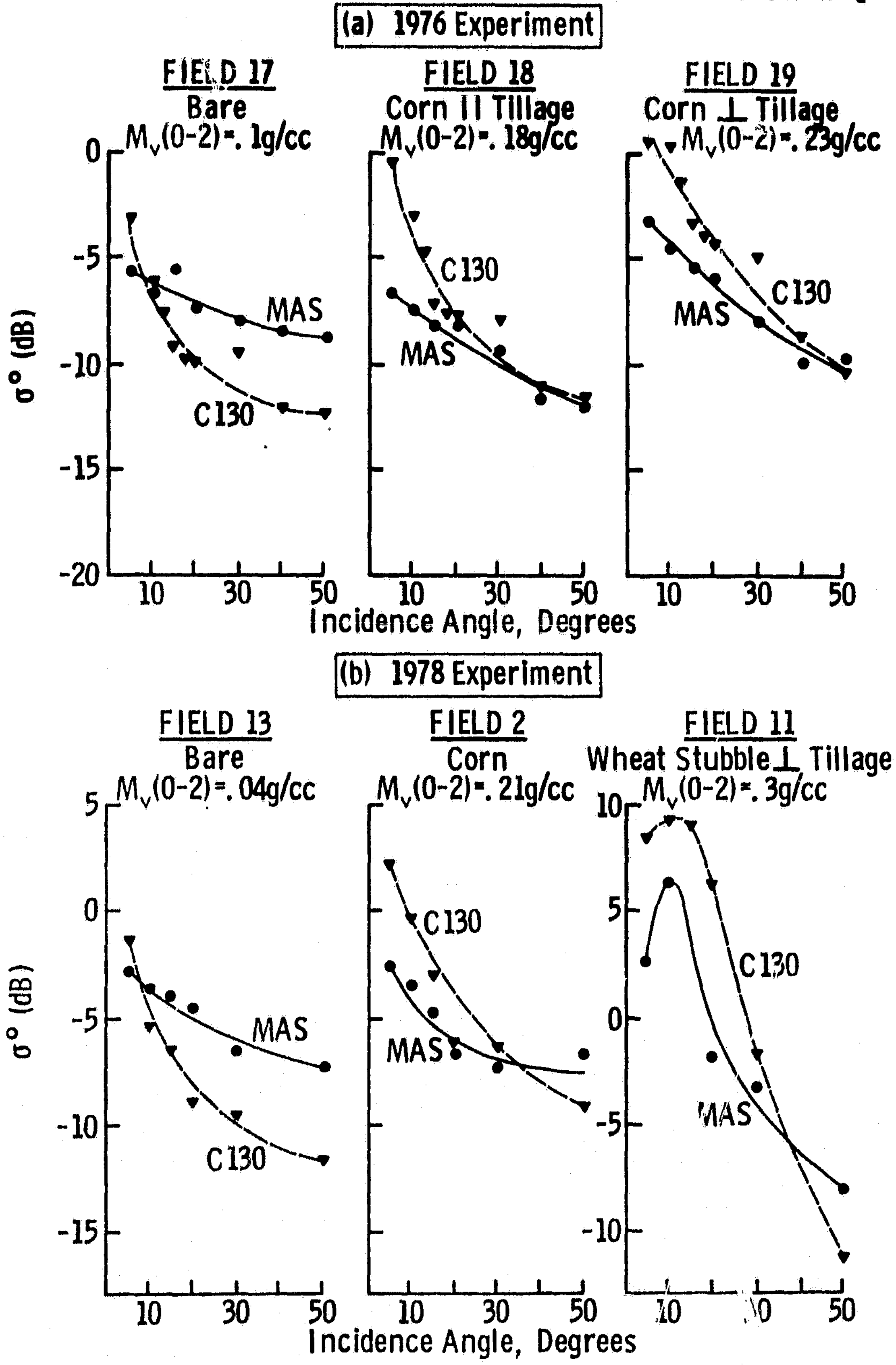
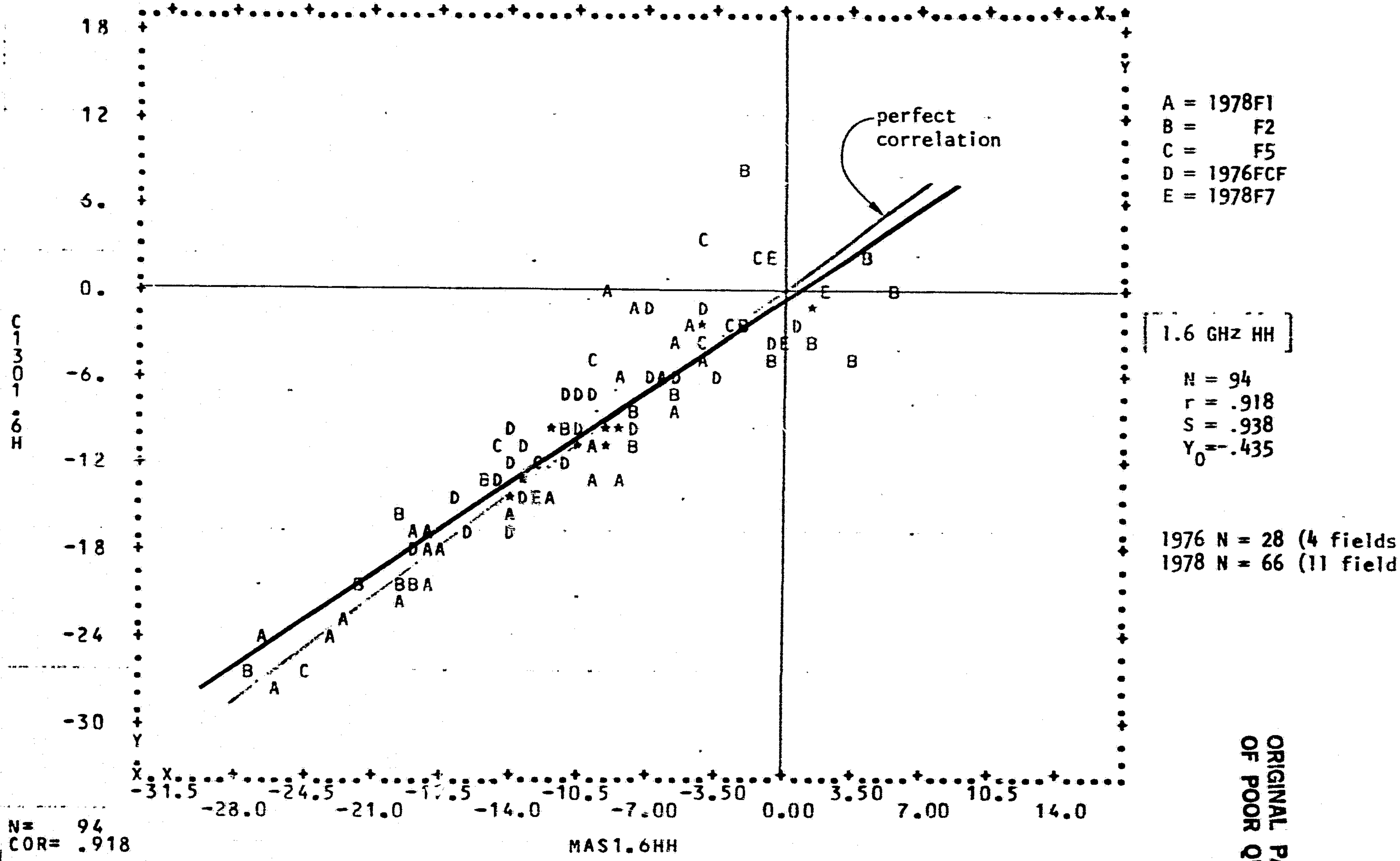
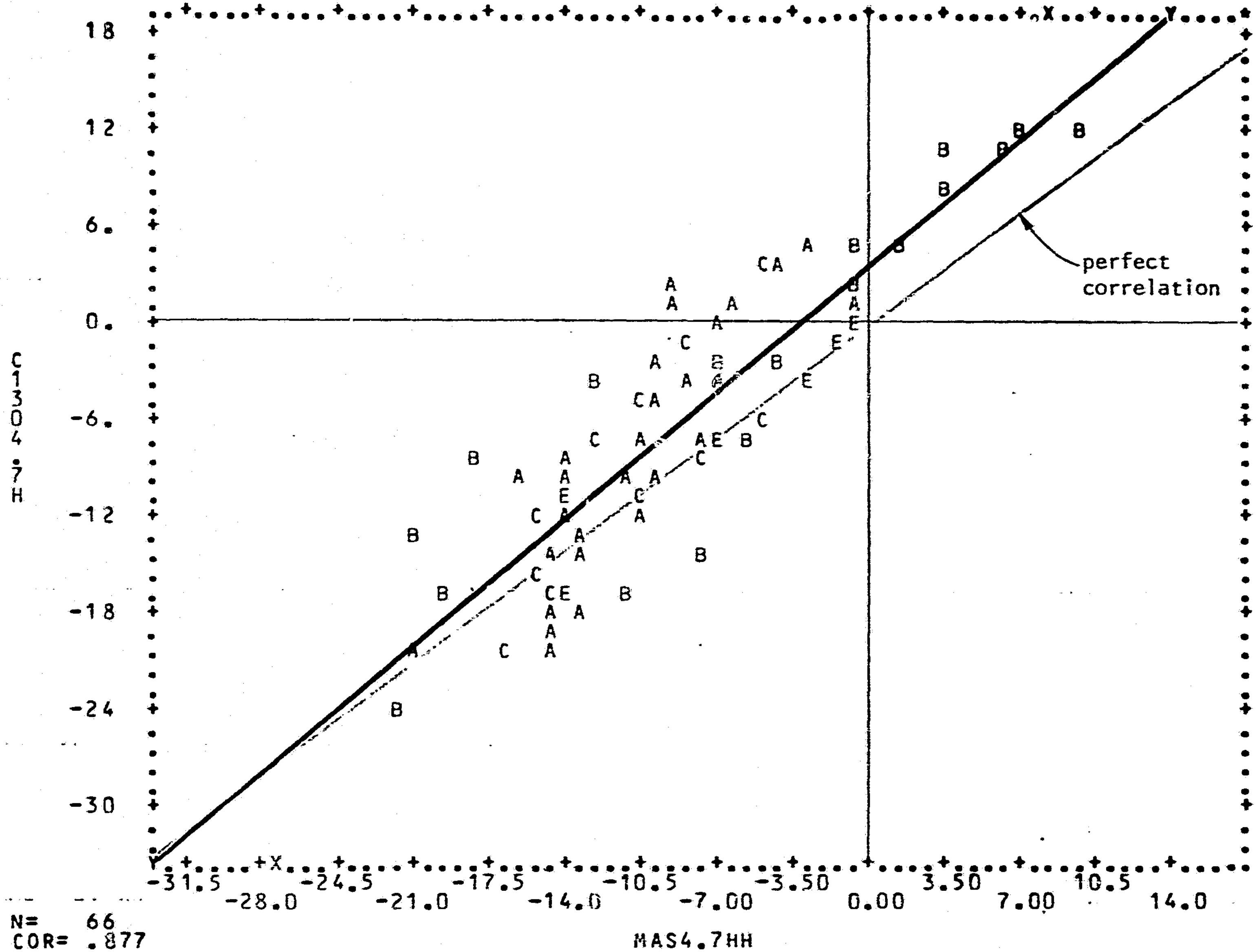


Figure 4. Comparison of 13.3GHz VV MAS and Aircraft Scatterometer Data for Various Terrain Types.



Regression of 1.6GHzHH aircraft scatterometer data and MAS data.

The correlation coefficient is .918.



A = 78F1
B = 78F2
C = 78F5
D = 7?F?F (none)
E = ??F7

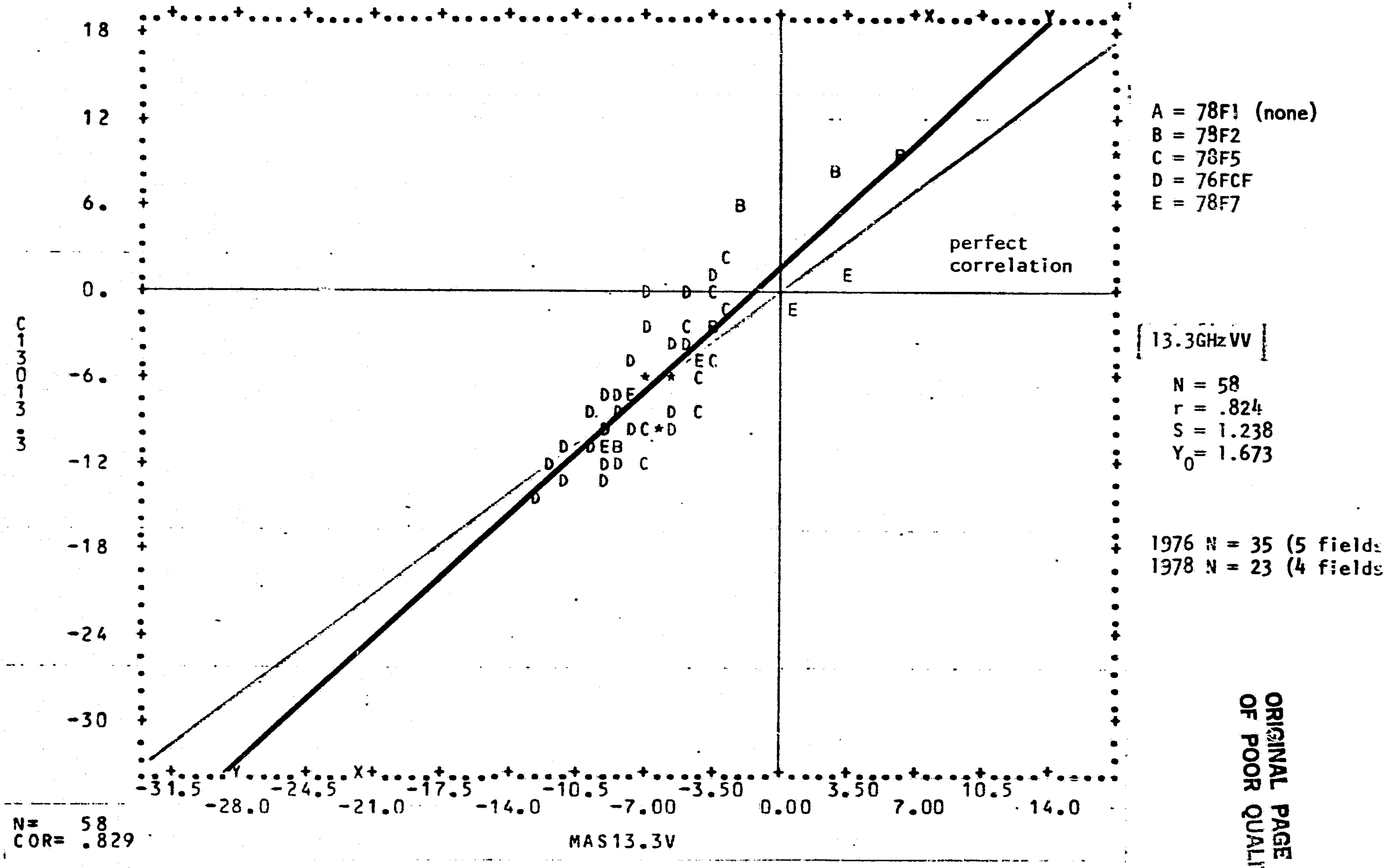
4.75GHzHH

N = 66
r = .877
s = 1.117
Y_0 = 3.52

1978 N = 66 (11 field

Regression of 4.75 GHzHH aircraft scatterometer data and MAS data.

The correlation coefficient is .877.



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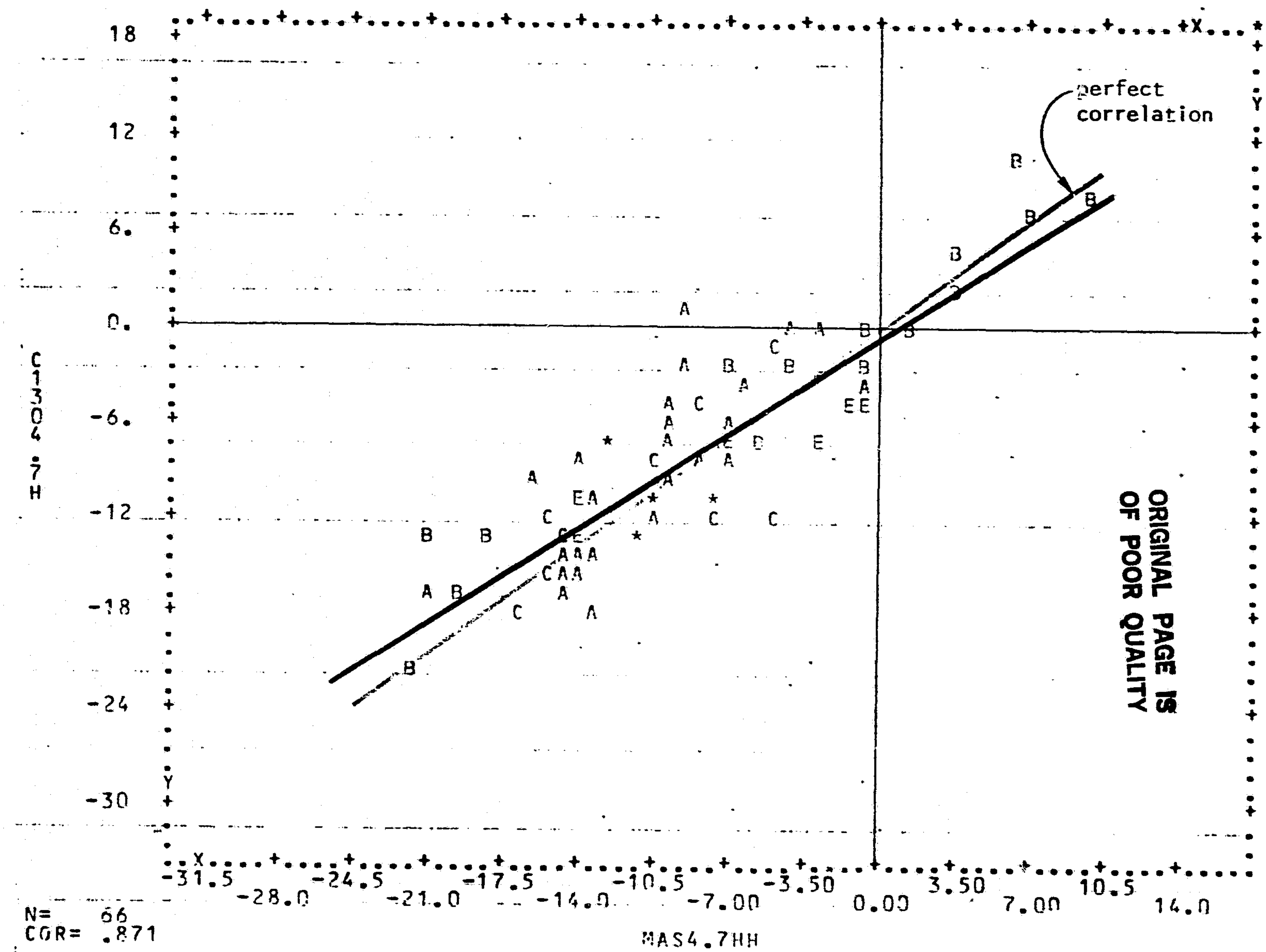
Regression of 13.3 GHz VV aircraft scatterometer data and MAS data.

The correlation coefficient is .829.



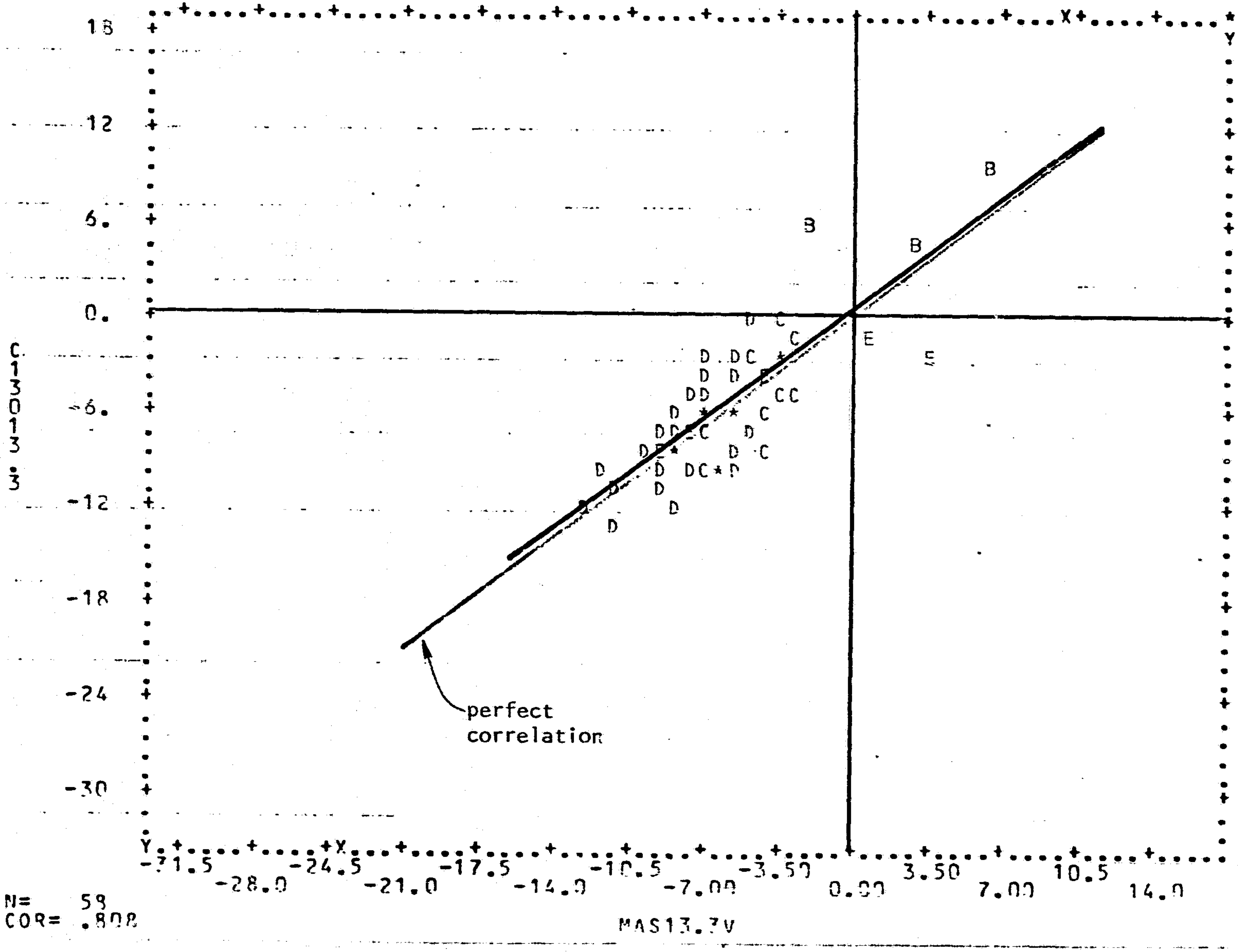
4.75 GHzHH

N = 66
r = .871
S = .868
Y_0 = -.42

C130 Calibration Factors

5°	5.2dB
10	4.2
15	3.9
[illegible]	0
30	0
50	3.1

Regression of 4.75 GHzHH Data with the calibration coefficients applied to the aircraft data.



13.3 GHz VV

N = 58
r = .808
S = 1.025
Y_0=.203

C130 Calibration Factors

5°	3.2dB
10	0
15	0
20	0
30	0
50	-2.4

Regression of 13.3 GHz VV Data with the calibration coefficients applied to the aircraft data.

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1978 AIRCRAFT RADAR DATA ANALYSIS

1. Flights 1 & 2

   a. Flight 1--7/18/78 Dry

   b. Flight 2--7/20/78 Wet (.75" rain on 7/19)

2. 25 Fields Analyzed to Date

   8 bare (4 tilled, 4 untilled)

   9 wheat stubble

   5 corn

   1 pasture

   1 alfalfa

   1 milo

3. 82 Data Sets Analyzed to Date

4. Remaining Sets on Flights 1 & 2

   10 fields

   19 data sets

→ 5. Need Flights 3-7 (total of ~350 data sets) ←

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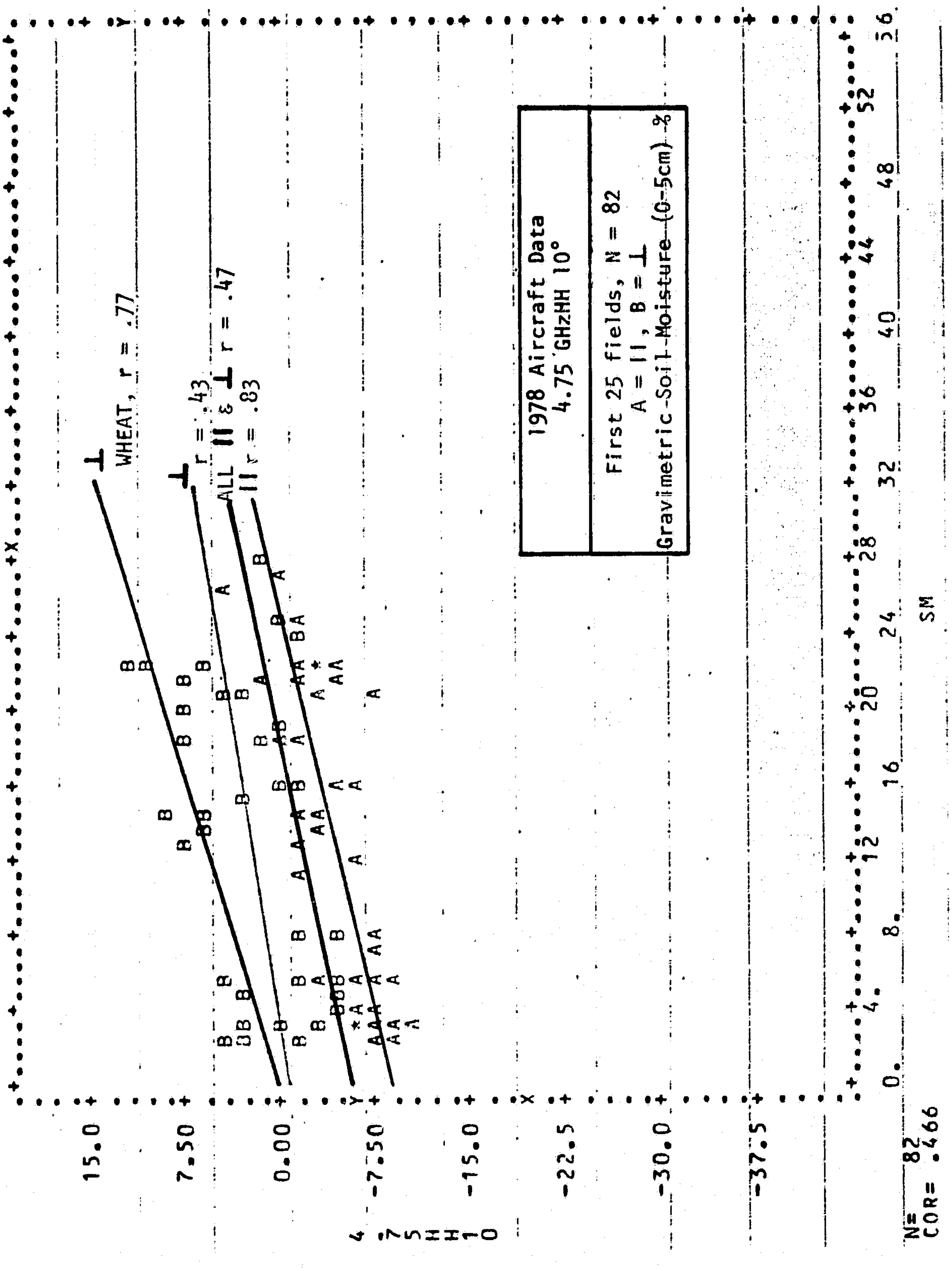
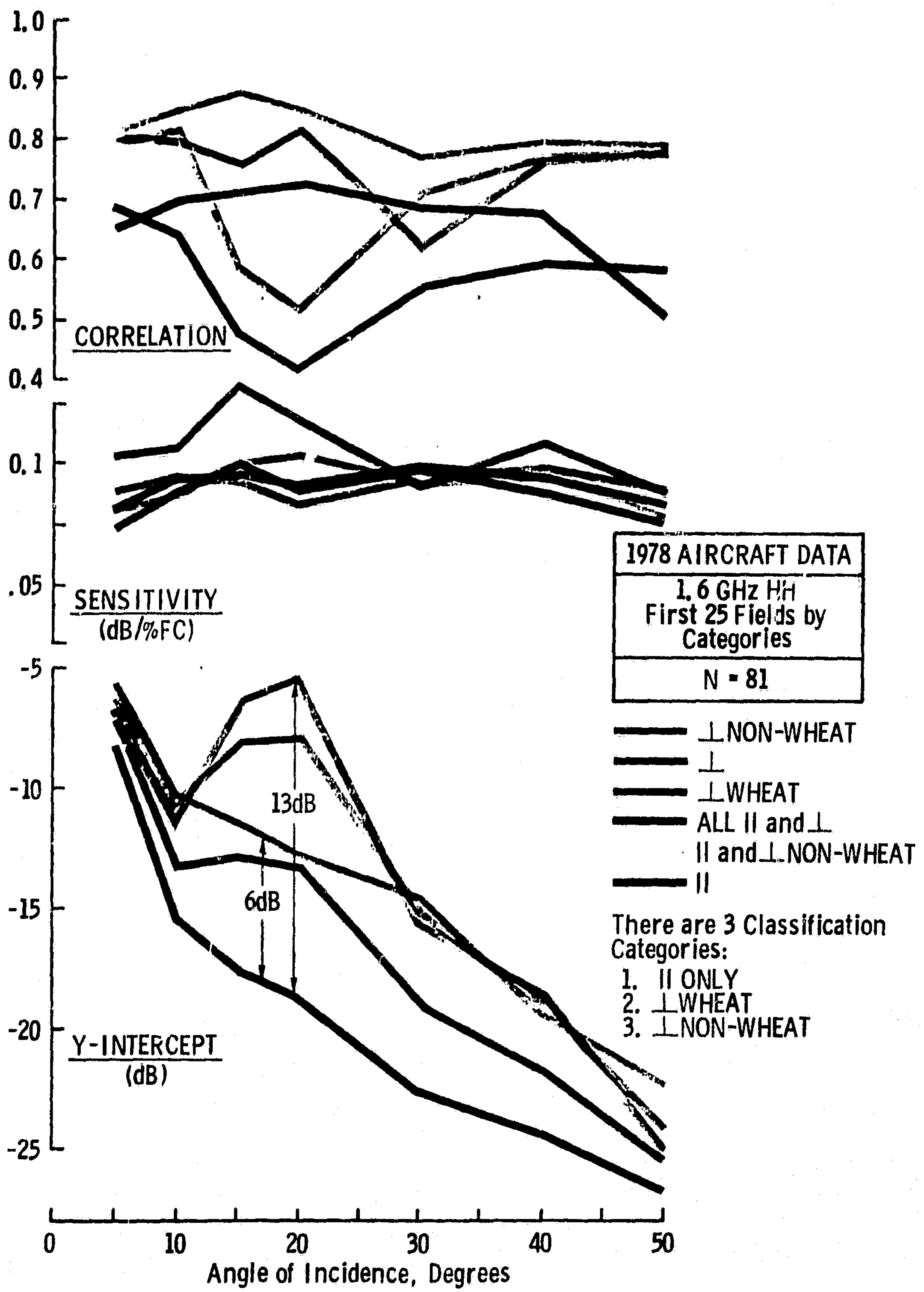
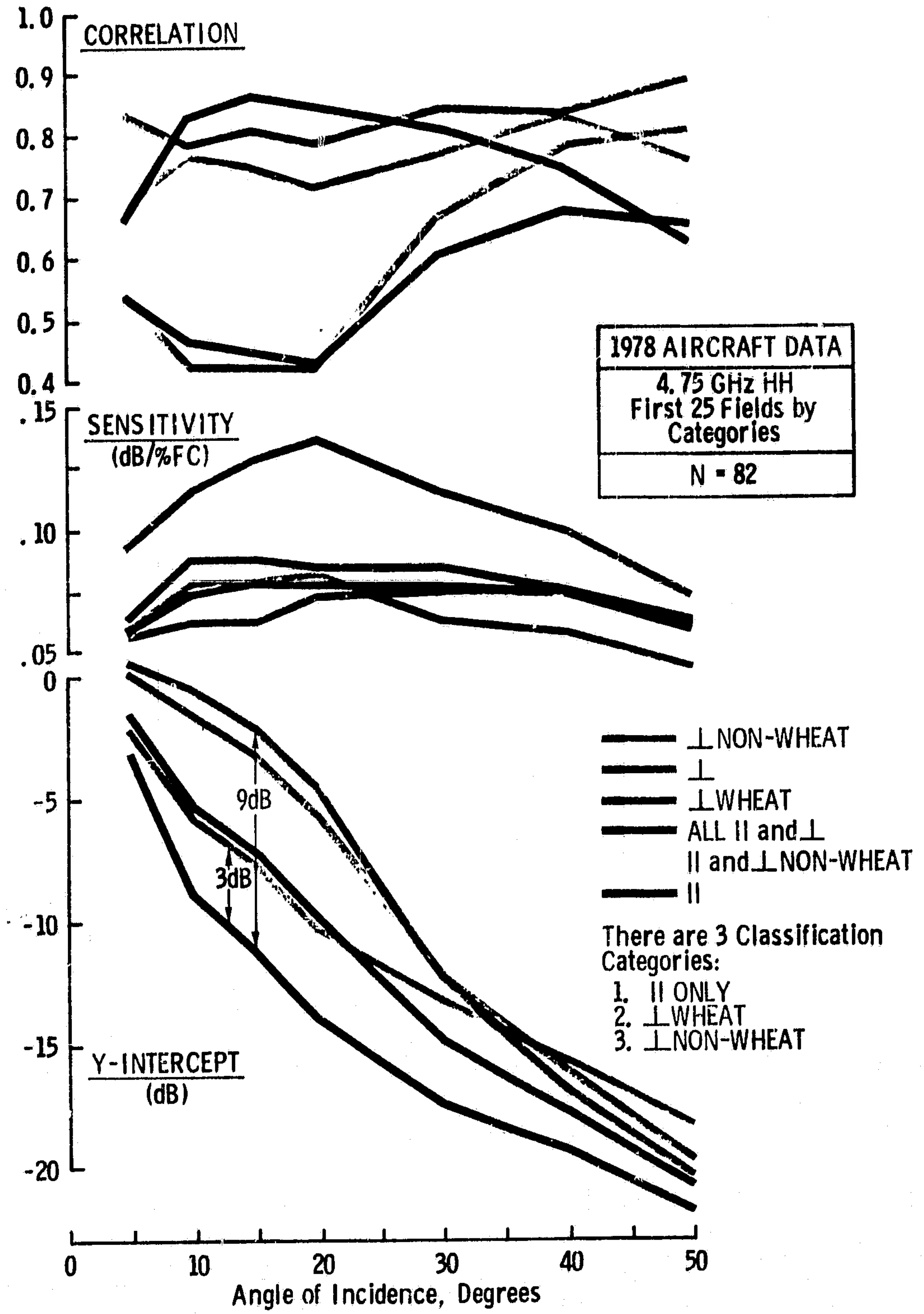



1.0
0.9
0.8
0.7
0.6
0.5
0.4
CORRELATION
0.1
.05
SENSITIVITY
(dB/%FC)
-5
-10
-15
-20
-25
Y-INTERCEPT
(dB)
13dB
6dB
0
10
20
30
40
50
Angle of Incidence, Degrees
1978 AIRCRAFT DATA
1.6 GHz HH
First 25 Fields by
Categories
N = 81
⊥ NON-WHEAT
⊥
⊥ WHEAT
ALL ∥ and ⊥
∥ and ⊥ NON-WHEAT
∥
There are 3 Classification
Categories:
1. ∥ ONLY
2. ⊥ WHEAT
3. ⊥ NON-WHEAT


1.0
CORRELATION
0.9
0.8
0.7
0.6
0.5
0.4
.15
SENSITIVITY
(dB/%FC)
.10
.05
0
-5
9dB
3dB
-10
-15
Y-INTERCEPT
(dB)
-20
0
10
20
30
40
50
Angle of Incidence, Degrees
1978 AIRCRAFT DATA
4.75 GHz HH
First 25 Fields by
Categories
N = 82
⊥NON-WHEAT
⊥
⊥WHEAT
ALL ∥ and ⊥
∥ and ⊥ NON-WHEAT
∥
There are 3 Classification
Categories:
1. ∥ ONLY
2. ⊥WHEAT
3. ⊥NON-WHEAT

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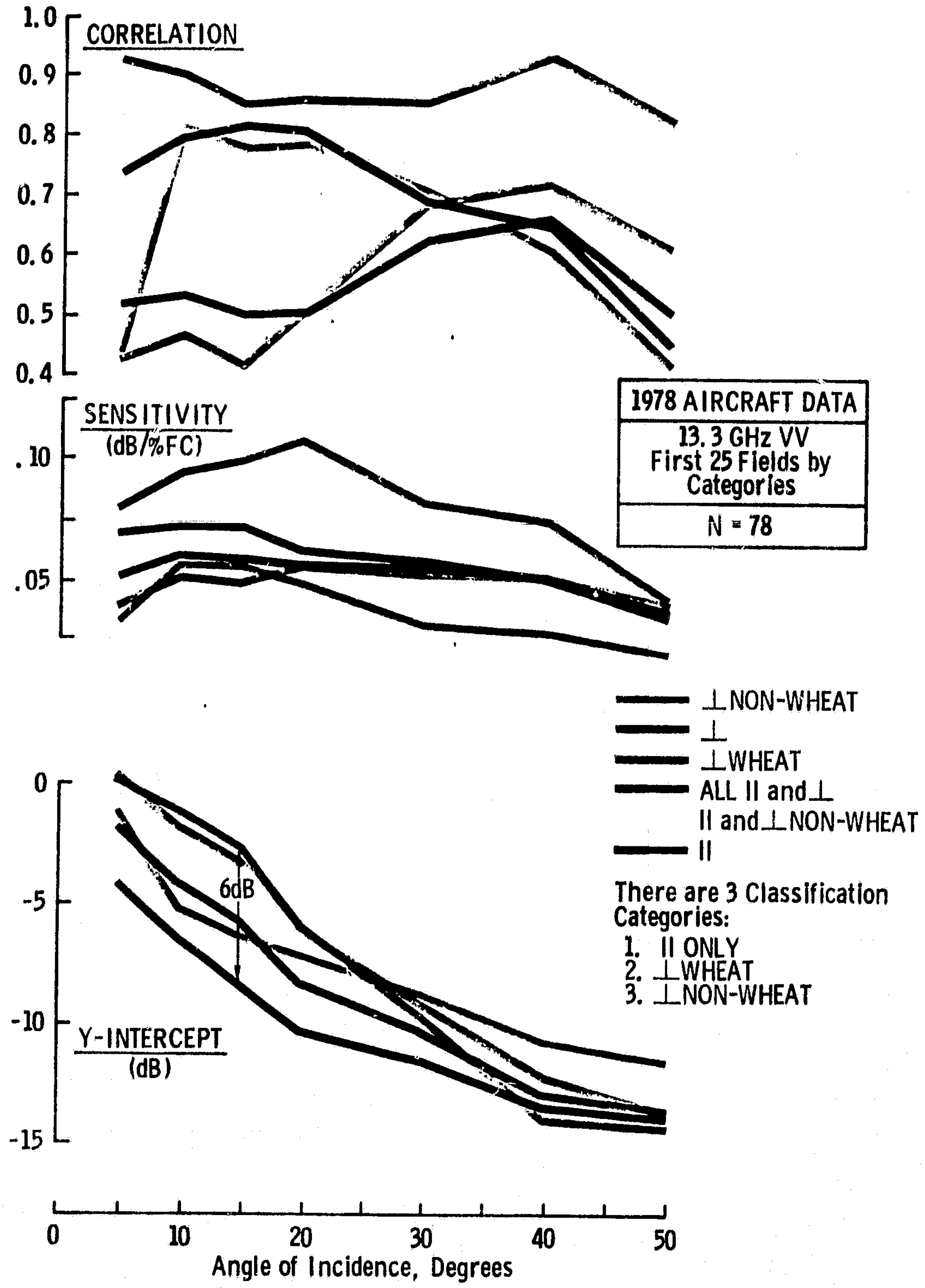

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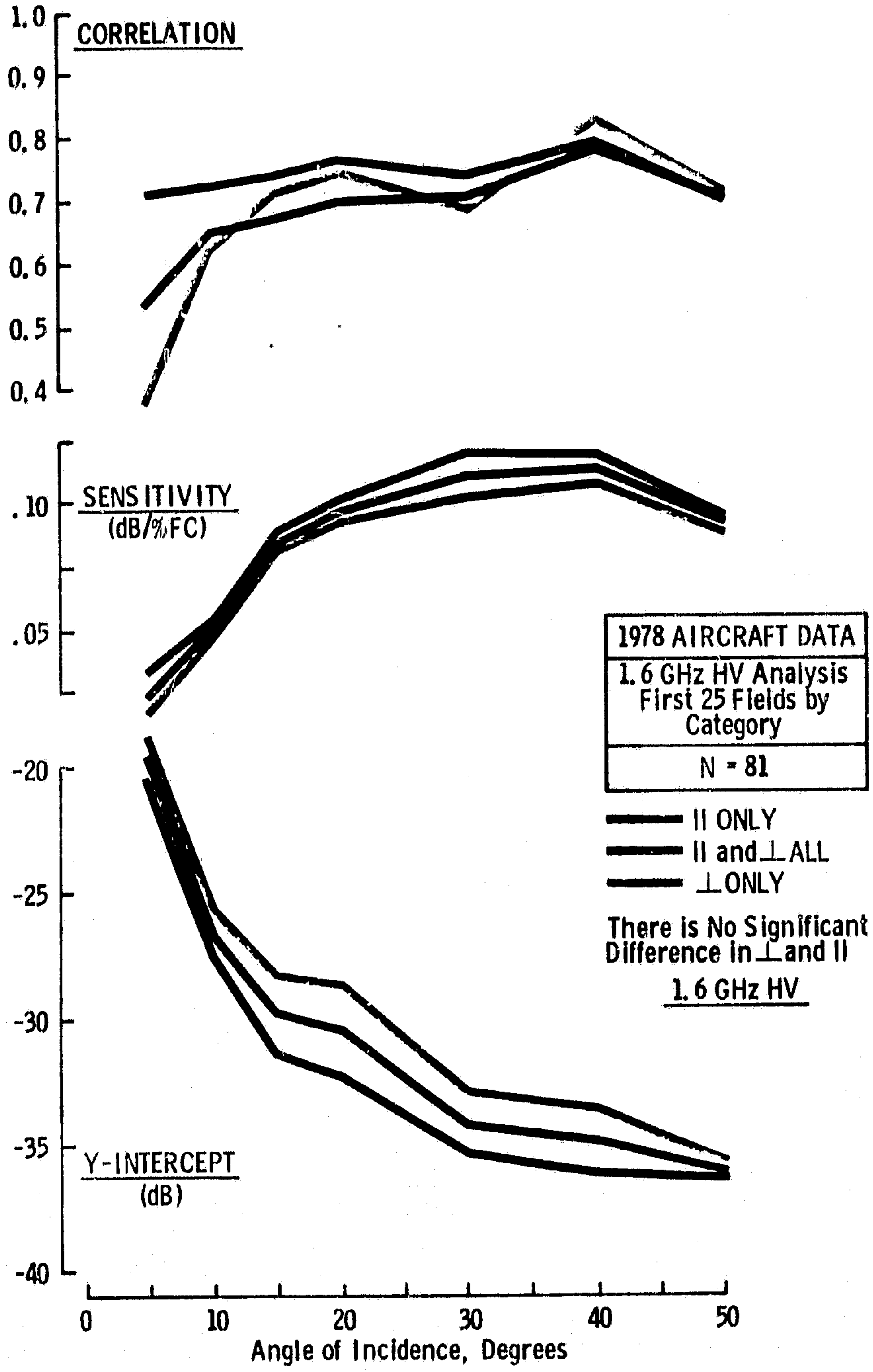

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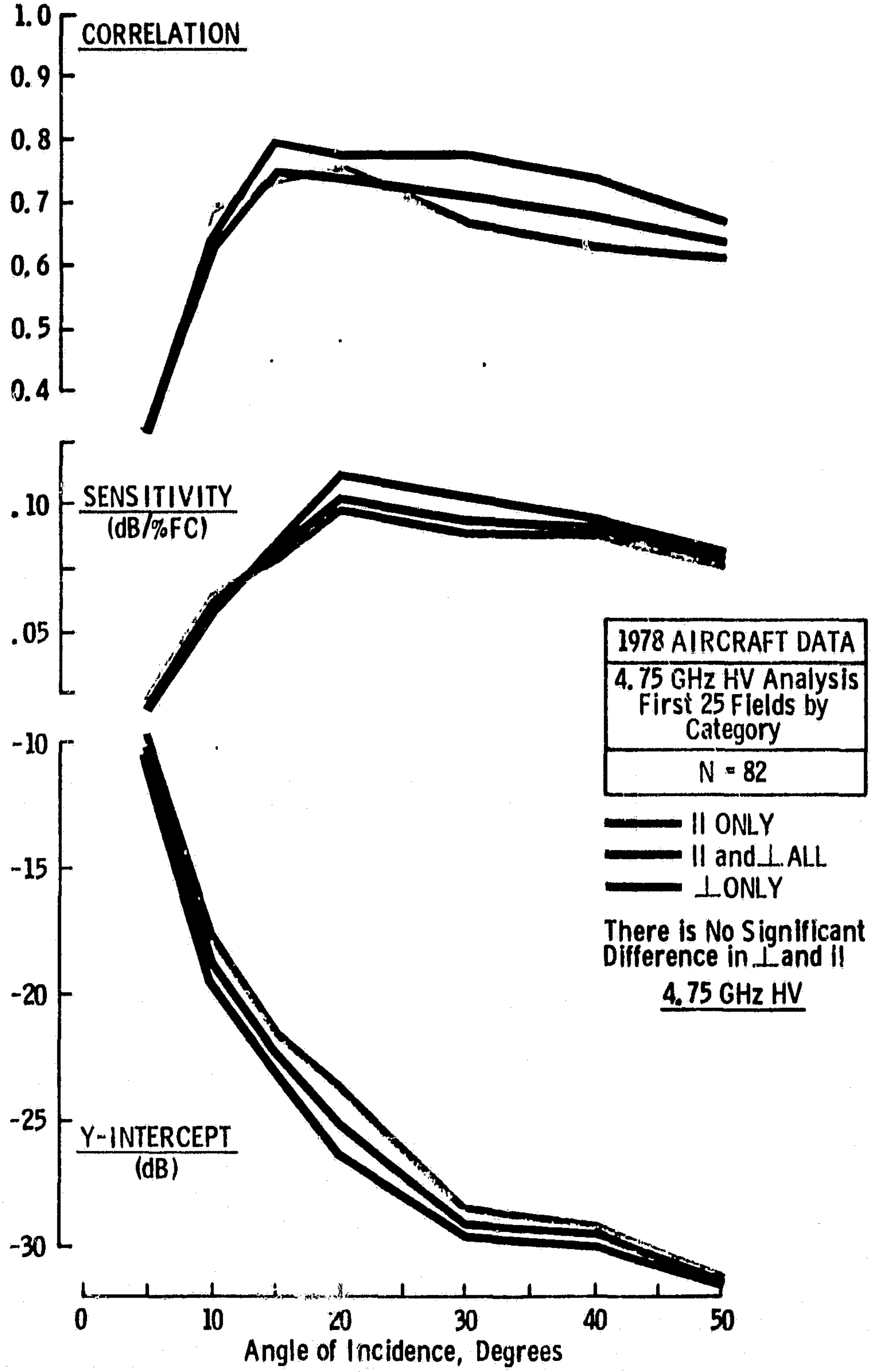
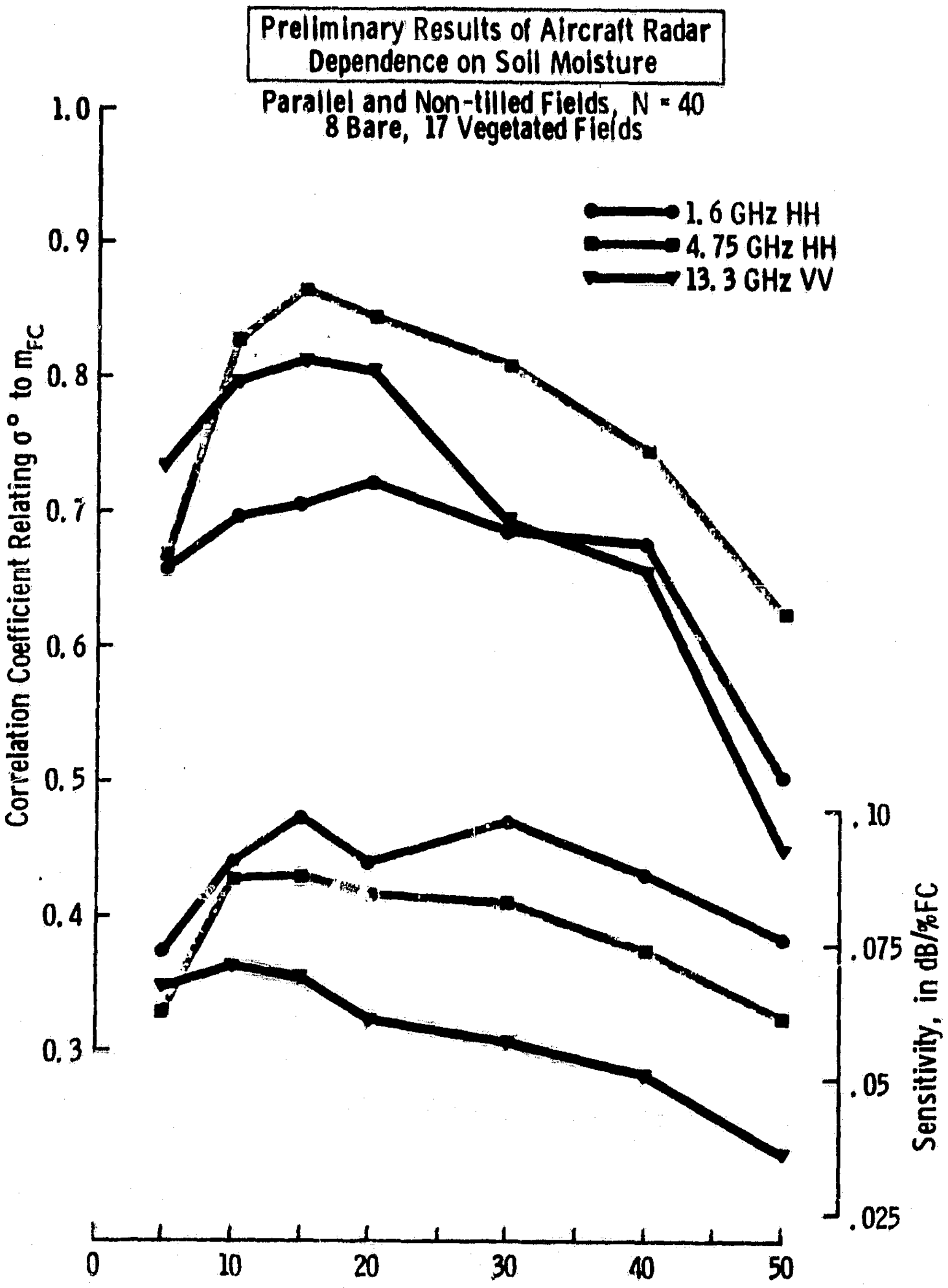
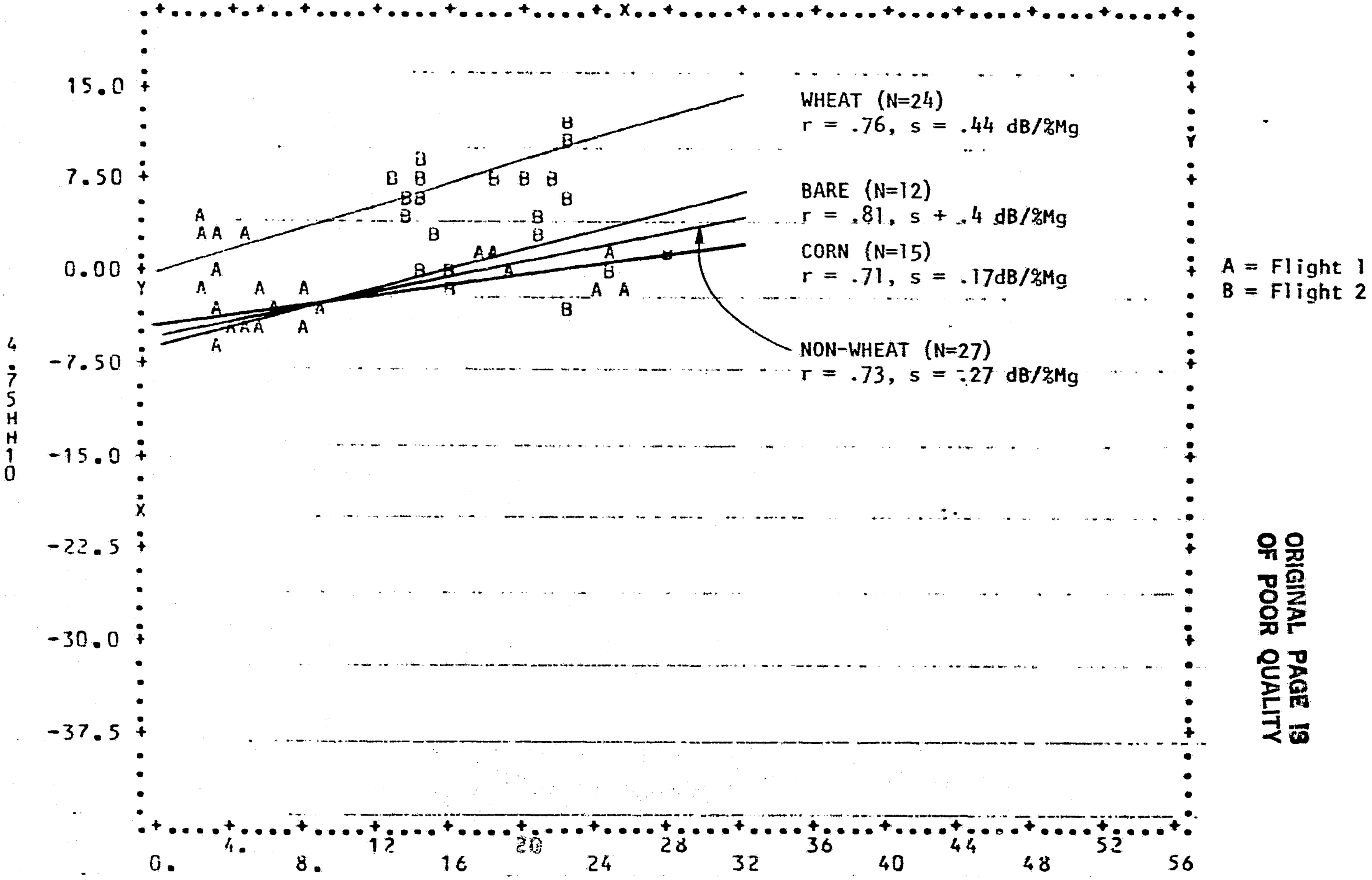
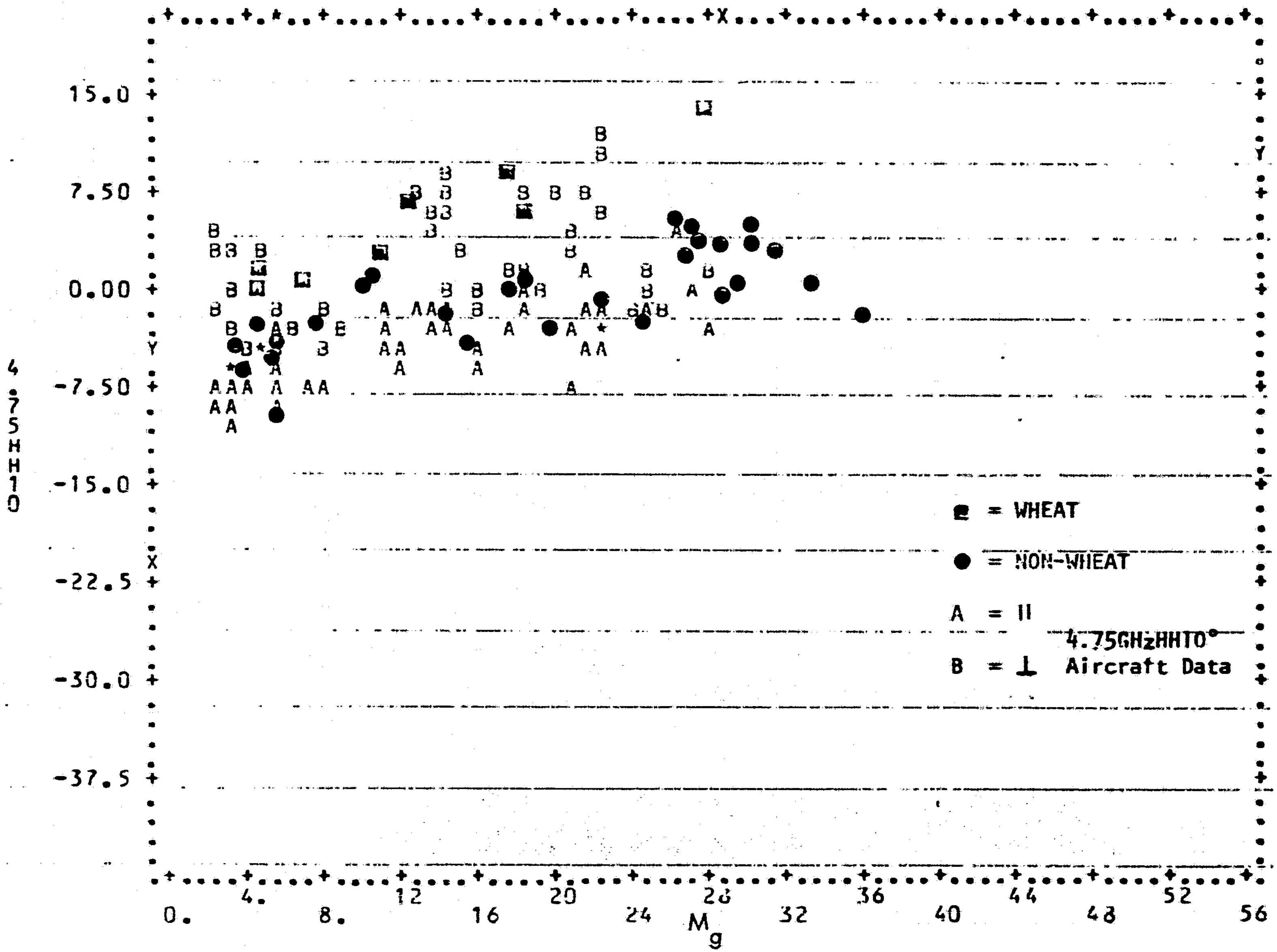



Preliminary Results of Aircraft Radar
Dependence on Soil Moisture
Parallel and Non-tilled Fields, N = 40
8 Bare, 17 Vegetated Fields
1.6 GHz HH
4.75 GHz HH
13.3 GHz VV
Correlation Coefficient Relating σ° to m_FC
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Sensitivity, in dB/%FC
.10
.075
.05
.025
0
10
20
30
40
50

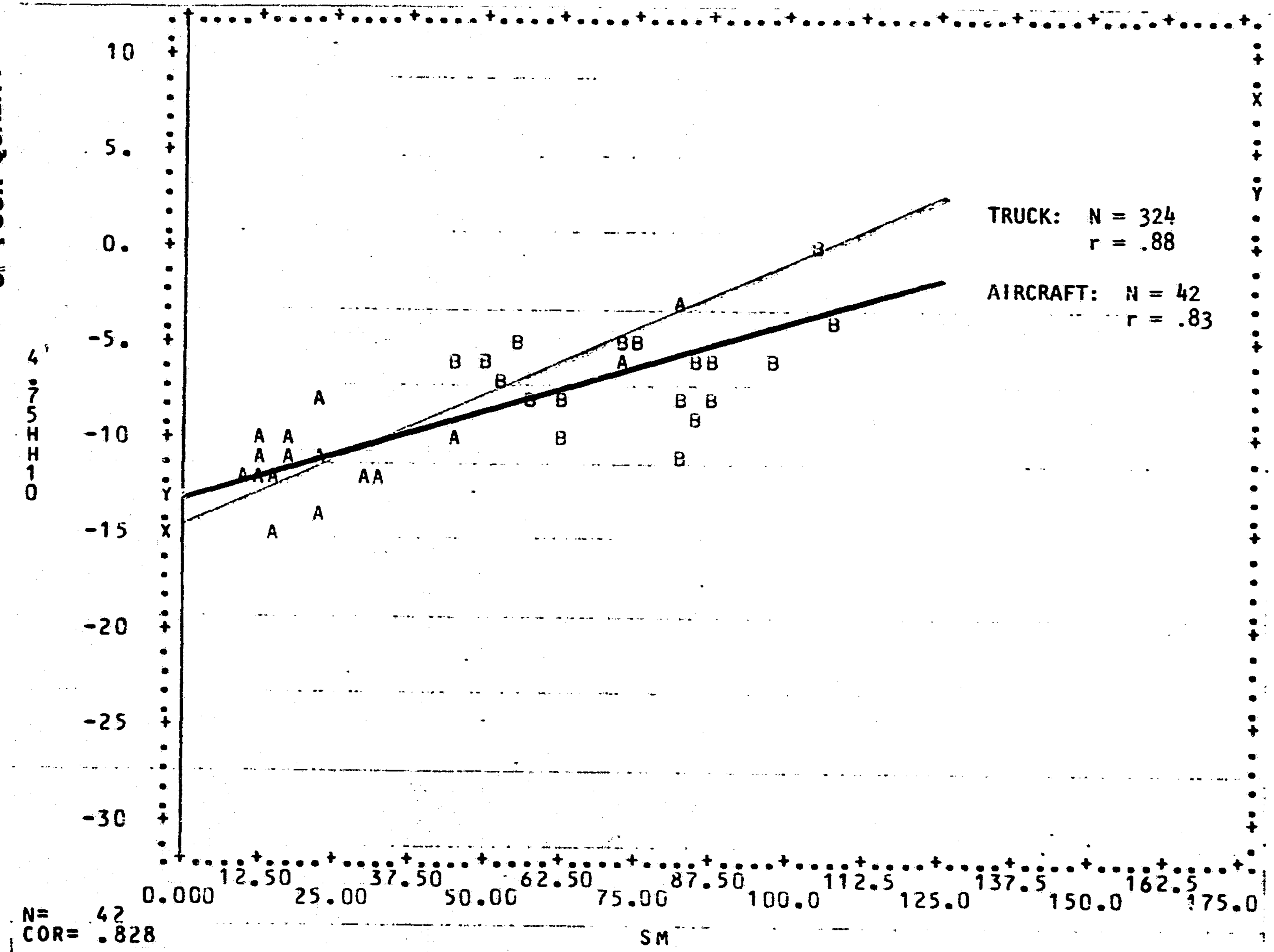


1978 Aircraft Data
4.75GHzHH 10°
First two flights ⊥ row direction, N = 51
Gravimetric Soil Moisture (0-5cm) %



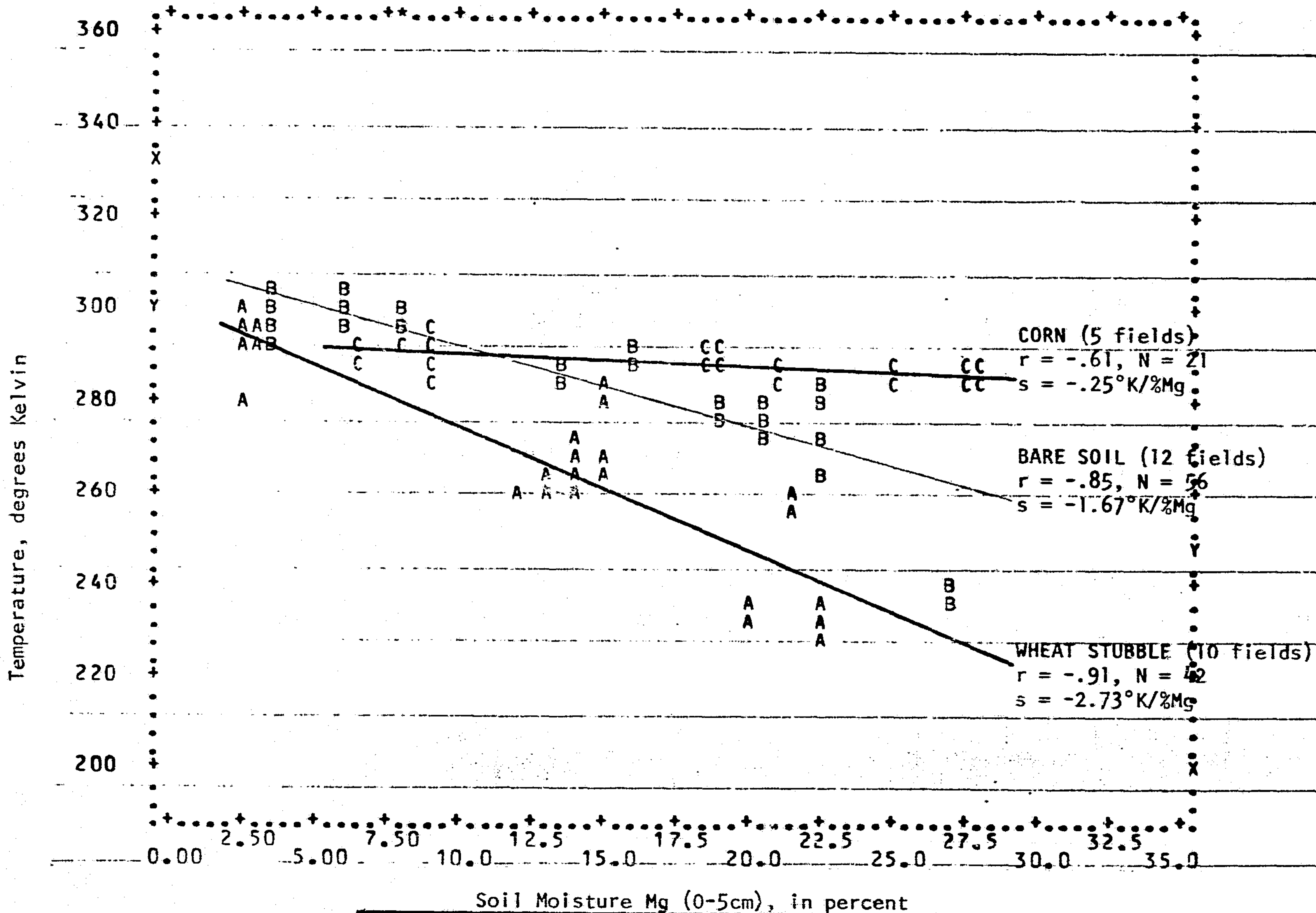
Comparison of 1978 MAS and Aircraft Data 4.75 GHzHH 10° N = 35

Calibration Factor = 4.2dB



Comparison of preliminary aircraft soil moisture algorithm and truck soil moisture algorithm.

(Aircraft corrected by -4.2dB)



1978 Aircraft C-Band Radiometer Preliminary Results

λ = 6cm, θ = 0°, 28 fields

H and V (no difference)

|| and ⊥ (no difference)

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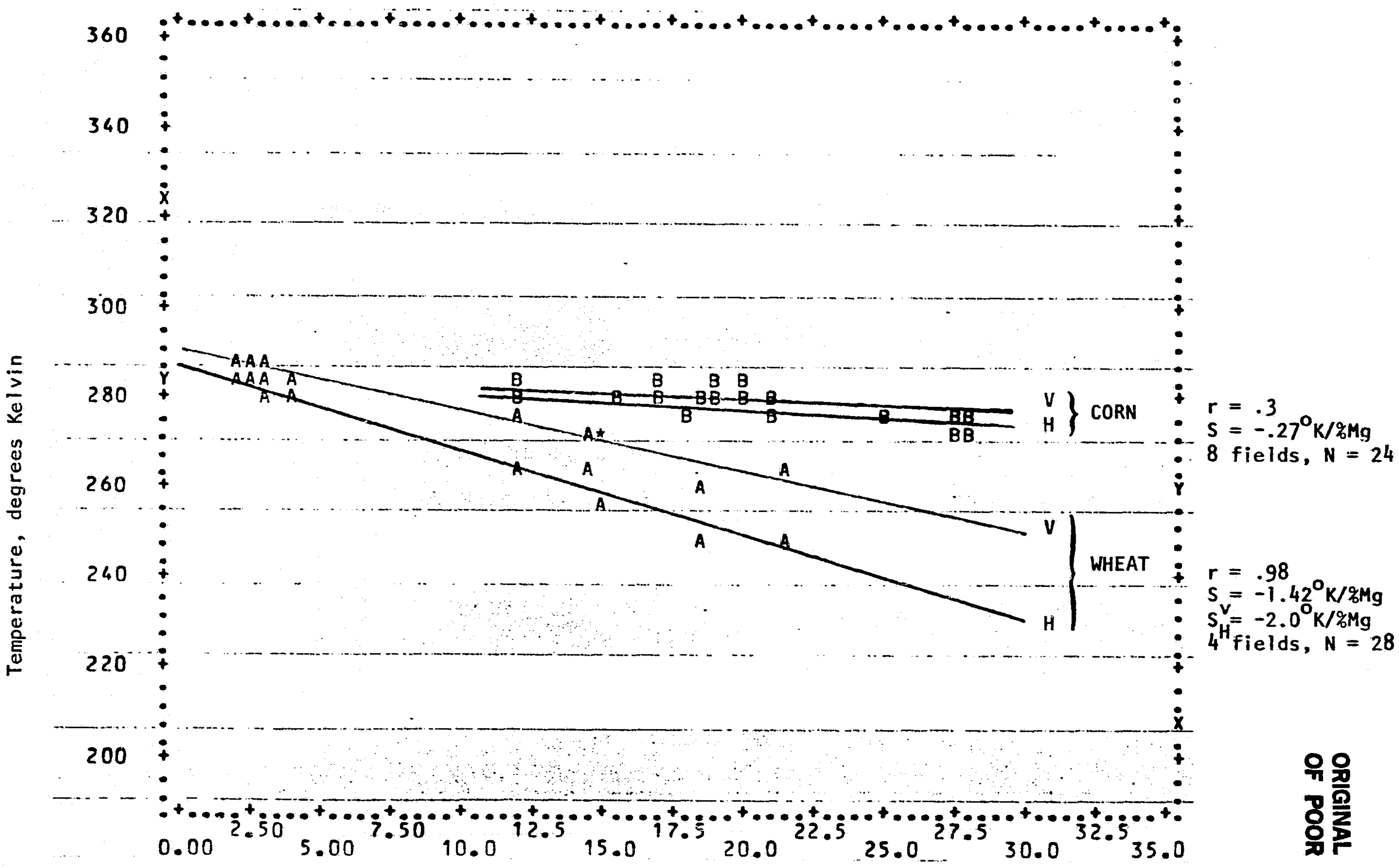

1978 Aircraft C-Band Radiometer

Preliminary Results

$\lambda = 6cm$, $\theta = 40^{o}$, 26 fields

|| and ⊥ combined (no difference)

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THE FUTURE

- 1978 Aircraft Data S. M. Algorithms
  - Radar
  - Radiometry
- 1979 Experiment Results
  - Optimum Soil Moisture Indicator
  - Temporal/Spatial Dependence
- 1980 Experiment
  - Row Direction
  - σ^o (f, P, θ) vs. tillage vs. α
- 1980 SLAR Experiment
- Dielectric Coefficient Research
- Radiometer/Radar Experiments
- Radar Soil Moisture Image Simulation

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